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A SYSTEMS ENGINEERING ANALYSIS OF UNMANNED MARITIME SYSTEMS FOR U.S. COAST GUARD MISSIONS

by

James B. Zorn

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Thesis Advisor:	Timothy H. Chung
Second Reader:	Mark Stevens

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14. ABSTRACT

The U.S. Coast Guard is uniquely suited to utilize multi-mission unmanned maritime systems (UMS) to maintain its leading role in maritime safety, security and stewardship. Current UMS technological capabilities coupled with USCG mission needs motivate an analysis of proposed USCG UMS through a systems engineering methodology. This work begins by decomposing the capability needs for USCG UMS by developing a series of concepts of operations (CONOPS) in a "solution neutral" context. Following capabilities analysis, multi-mission commonalities help derive three USCG UMS alternatives: (1) Cutter-Based Tactical UUV, (2) Shore-Based Harbor/Coastal UUV/USV, and (3) Operational Offshore USV. These alternatives and their respective system architectures provide a design concept for near- to mid-term (5-10 year) acquisition. Finally, feasibility analysis reviews key system enablers (such as technology, capability, policy, and supportability and manpower) for the alternatives to justify a realistic integration timeline. Recommendations for technology investments, enhanced UMS partnerships, USCG unmanned system policies and organizational knowledge are provided to reduce delays and to accelerate delivery of needed capabilities to the field. This study lays the foundation for future strategic planning of USCG UMS (i.e., a USCG UMS Roadmap) while providing additional motivation for USCG unmanned systems in general.

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James B. Zorn
Lieutenant, United States Coast Guard
B.S., United States Merchant Marine Academy, 2008

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June 2013

Author: James B. Zorn

Approved by: Timothy H. Chung
Thesis Advisor

Mark Stevens
Second Reader

Cliff Whitcomb
Chair, Department of Systems Engineering

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The U.S. Coast Guard is uniquely suited to utilize multi-mission unmanned maritime systems (UMS) to maintain its leading role in maritime safety, security and stewardship. Current UMS technological capabilities coupled with USCG mission needs motivate an analysis of proposed USCG UMS through a systems engineering methodology. This work begins by decomposing the capability needs for USCG UMS by developing a series of concepts of operations (CONOPS) in a "solution neutral" context. Following capabilities analysis, multi-mission commonalities help derive three USCG UMS alternatives: (1) Cutter-Based Tactical UUV, (2) Shore-Based Harbor/Coastal UUV/USV, and (3) Operational Offshore USV. These alternatives and their respective system architectures provide a design concept for near- to mid-term (5-10 year) acquisition. Finally, feasibility analysis reviews key system enablers (such as technology, capability, policy, and supportability and manpower) for the alternatives to justify a realistic integration timeline. Recommendations for technology investments, enhanced UMS partnerships, USCG unmanned system policies and organizational knowledge are provided to reduce delays and to accelerate delivery of needed capabilities to the field. This study lays the foundation for future strategic planning of USCG UMS (i.e., a USCG UMS Roadmap) while providing additional motivation for USCG unmanned systems in general.

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Table of Contents

List of Figures

List of Tables

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List of Acronyms and Abbreviations

AIS Automatic Identification System
AOR Area of Responsibility
ATON Aids to Navigation
CBP Customs and Border Protection
COLREGS Collision Regulations
CONOPS Concept of Operations
DI Drug Interdiction
DHS Department of Homeland Security
DOD Department of Defense
DR Defense Readiness
EEZ Economic Exclusive Zone
HSI Human System Integration
IO Ice Operations
ISR Intelligence, Surveillance, and Reconnaissance
KSE Key System Enabler
LMR Living Marine Resource
MEP Marine Environmental Protection
MI Migrant Interdiction
MS Maritime Security
MSAF Marine Safety
MUT Manned-Unmanned Teaming
NAIS Nationwide Automatic Identification System
NPS Naval Postgraduate School
OLE Other Law Enforcement
PWCS Ports, Waterways, & Coastal Security
RACON Radar Beacon Transponder
ROV Remotely Operated Vehicle
SAR Search and Rescue
SE Systems Engineering
TRL Technology Readiness Level
UAV Unmanned Ariel Vehicle
USC U.S. Code
USCG United States Coast Guard
USG United States Government
USN United States Navy
UMS Unmanned Maritime System
UMV Unmanned Maritime Vehicle
USV Unmanned Surface Vehicle
UUV Unmanned Underwater Vehicle

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Executive Summary

To maintain the U.S. Coast Guard's (USCG) role as the nation's premier maritime authority, it is necessary to explore and analyze unmanned maritime vehicles (UMV) as crucial system technologies to enhance and augment USCG mission capabilities. Utilizing a holistic systems engineering approach to conduct research and analysis, this work provides a notional time line for the acquisition of USCG Unmanned Maritime Systems (UMS), and ultimately lays the foundation for a strategic roadmap.

Key drivers for this research are the need for a timely injection of capabilities due to emerging maritime threats and obsolescent USCG assets in tandem with recent advances in UMS technologies. The USCG has several critical assets such as *Polar* class icebreaking cutters that are nearing or past the end of their predicted service life. In addition to aging assets, emerging threats and enemy capabilities challenge mission effectiveness. Notably, there is an unprecedented increase in Intelligence, Surveillance, and Reconnaissance (ISR) capability needs which are critical to maintaining maritime domain awareness (MDA). There also exists a host of new demands in strategic regions such as the Arctic. Meanwhile UMS Technology Readiness Levels (TRL) are rapidly increasing, and many commercial off-the-shelf (COTS) variations are available and used throughout the world for military, scientific, and commercial applications.

This work views UMS from a domain neutral perspective during conceptual analysis because surface and undersea vehicles can offer similar capabilities, and it has been said to be more beneficial to study their applications together than separately. Regardless of domain, UMSs are capable of providing broad benefits unique to unmanned systems such as the reduction of operational mission risk by limiting personnel hazards in the treacherous maritime environment.

A tailored systems engineering process model provides the methodology to analysis USCG UMS in its conceptual phase. The methodology begins by identifying the effective needs of the USCG in general and with regard to UMS. Generally, concepts of operations are developed into mission packages including Aids to Navigation, Maritime Security, Living Marine Resources, Marine Environmental Protection, Search and Rescue and Marine Safety. Desired capabilities for these CONOPS and their mission package variations show commonalities across missions. Persistence capabilities present the largest influence in grouping missions possible in one type of UMS.

The capabilities and concepts inform derived USCG UMS alternatives: (1) Cutter-Based Tac-

tical UUV, (2) Shore-Based Harbor/Coastal UMV, and (3) Operational Offshore USV. These represent a culmination of multi-mission capabilities, (near) proven technologies, and operational areas. Sensitivity analysis of design and operational characteristics provides additional realism. High-level USCG UMS system architectures, functional and physical, reinforced the systems approach and relationships between operational, functional, and physical perspectives. The commonality of high-level functions seen in the USCG UMS master functional hierarchy supports modularity of certain UMS technologies, such as acoustic vessel identification and classification. Investment in those types of technologies would provide value across UMS alternatives. This understanding supports a open architecture development framework seen throughout the UMS industry, and promises to take advantage of commercial and military UMS advances over the course of USCG UMS life-cycle.

Finally, a survey of existing UMS feasibility documents and roadmaps helps inform the USCG UMS timeline based on the derived alternatives and key system enablers. Interestingly, the vehicle platforms for every alternative are currently technologically mature, although some technological capabilities for perception and power density are still immature. Policy and supportability and manpower considerations are also immature, albeit less costly to improve than perception technologies. The timeline provides a USCG decision maker with a system-level view of current and anticipated USCG UMS feasibility and identifies areas for additional investment and research discussed in the Recommendations section of this work.

The systems engineering approach utilized in this work offers a framework for future iterations that are focused on strategic UMS applications rather than strictly asset or program specific implementations and short term fixes. Though a future strategic roadmap requires the input of numerous stakeholders, this work provides a strong motivation for the initiation of such a project and clear assessment for USCG UMS adoption.

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CHAPTER 1:
Introduction

In today's world, U.S. Coast Guard (USCG) mission capabilities are challenged by emerging threats in the maritime domain, aging USCG assets, and limited resources. *The U.S. Coast Guard Strategy for Maritime Safety, Security, and Stewardship* has stated a "Flexible, adaptable operational capability and presence" as one of its three key strength areas for meeting tomorrow's challenges [16]. Fortunately, this need can be fulfilled through a systems approach to the use and application of promising technologies that offer support, augmentation and enhancement to current USCG assets. Of the rapidly advancing technologies, unmanned maritime systems (UMS), including a unmanned surface vehicles (USV), unmanned underwater vehicles (UUV) or a combination thereof, present feasible and effective materiel solutions to enable a wide range of USCG missions. A thorough review, analysis, and vision of future USCG UMS is warranted to fully explore solutions to the service's needs.

1.1 Background

1.1.1 U.S. Coast Guard Overview

Over the past two centuries, the USCG has evolved into a multi-mission, military, and maritime organization with three major roles: Maritime safety, security, and stewardship. In 2003, it was transferred to the Department of Homeland Security (DHS) while maintaining its existing eleven statutory missions. Considering this organizational shift and national need for enhanced security priorities, several DHS missions are supported directed by the USCG, while others are considered "non-homeland security" and unique within a DHS agency, such as Search and Rescue or Marine Safety [1]. Figure 1.1 depicts the multi-mission nature of the USCG and their areas of commonality.

1.1.2 Jurisdiction and Authority

The USCG carries out its statutory missions over the world's largest national maritime domain, encompassing over 100,000 nautical miles of coastline and inland waterways [3]. Extending roughly 200 miles from all U.S. coastlines, the service is responsible for the approximate 3.4 million square nautical miles of ocean known as the U.S. Exclusive Economic Zone (EEZ). The U.S. establishment of an EEZ is fairly recent (1983) which significantly expanded on traditional maritime boundaries such as the 12 nautical mile territorial sea [17]. The EEZ is of special

Figure 1.1: Multi-mission integration is seen throughout the USCG at the strategic, operational, and tactical level. Most USCG assets are designed to provide capabilities for several missions at once. From [1].

significance because of the national "rights, jurisdiction, and duties." As codified by 33 CFR 2.30 and international law, the U.S. has:

> (a) sovereign rights for the purpose of exploring, exploiting, conserving and managing natural resources, both living and non-living, of the seabed and subsoil and the superjacent waters and with regard to other activities for the economic exploitation and exploration of the zone, such as the production of energy from the water, currents and winds; and (b) jurisdiction with regard to the establishment and use of artificial islands, and installations and structures having economic purposes, and the protection and preservation of the marine environment.

Maritime Environmental Protection (MEP) and Living Marine Resources (LMR) missions are implicitly stated, but security-related missions are equally as important and becoming a growing concern economically and militarily [18]. Also, U.S. non-continental states and territories extend the EEZ to encompass vast expanses of the Pacific ocean and the Arctic. Figure 1.2

provides a global map of the U.S. EEZs, the majority of these zones are far from the largest U.S. commercial and military populations, including traditional USCG assets.

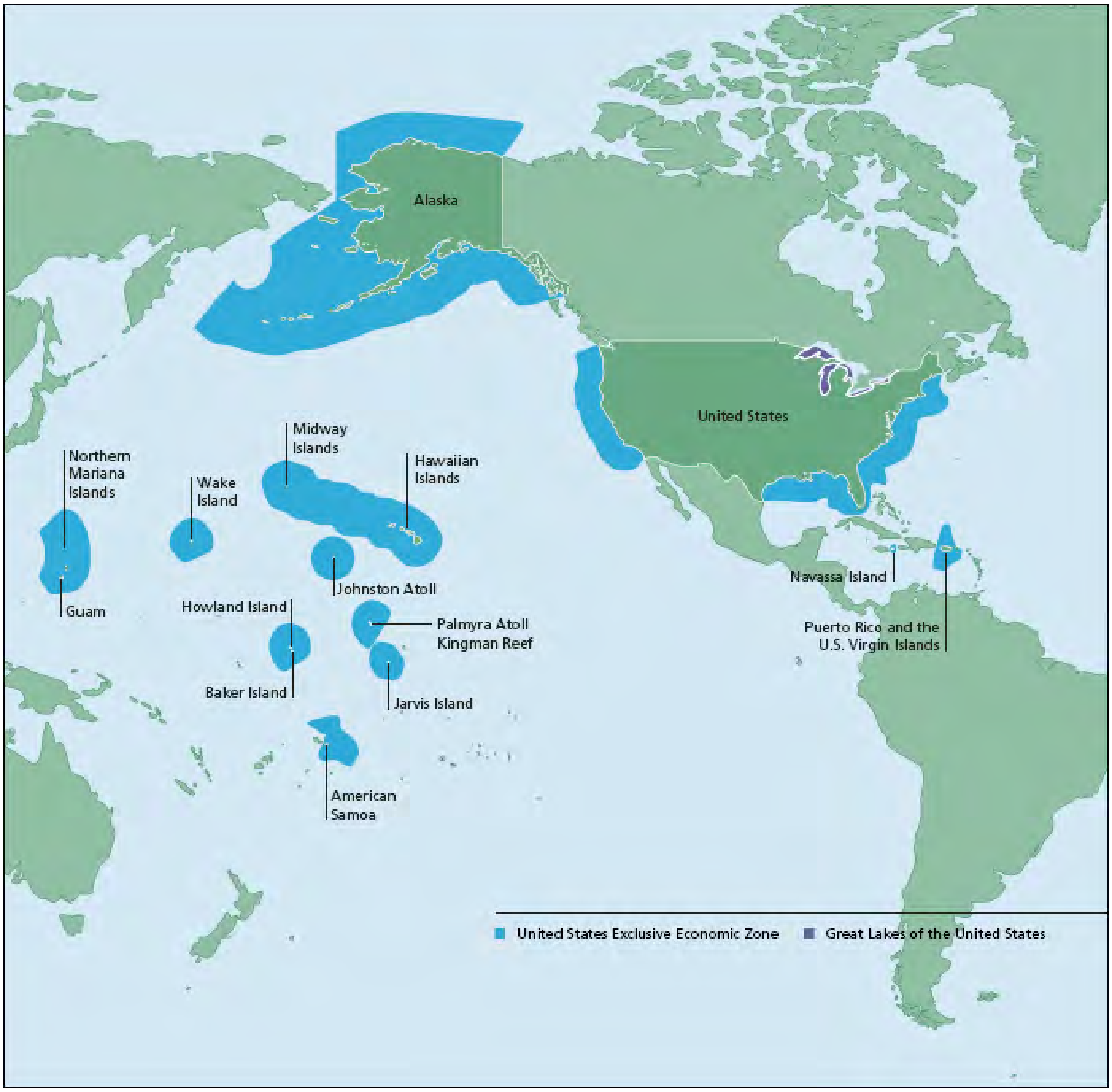

Figure 1.2: USCG jurisdiction extends throughout the entire U.S. Economic Exclusive Zone. Large expanses of Pacific and Arctic regions with little oversight present threats for the U.S. such as illegal harvesting of natural resources. From [2].

To accomplish this diverse set of missions, the USCG has some of the most unique authorities for any armed service or coast guard throughout the world. The combination of U.S. Code (USC) Title 10 Armed Force and USC 14 Coast Guard authorities establishes it as "a first

responder, a law enforcement organization, a regulatory agency, and an armed force." This distinction is of particular significant due to the Posse Comitatus Act which prohibits members of the Armed Forces from exercising law enforcement agency powers. Considering this, the USCG is mutually charged with both military missions (maritime security) and law enforcement missions. In addition to this, other unique authorities include Conservation (USC16), Customs Duties (USC 19), Navigation and Navigable Waters (USC 33), Comprehensive Environmental Response, Compensation, and Liability act (CERCLA), Public Lands (USC 43), Shipping (USC 46), and War and National Defense (USCG 50) among others.

USCG's role as a Maritime Regulator

The USCG administers and enforces navigation rules and regulations within U.S. waters for foreign and domestic vessels. In addition, The USCG has broad authority over the undersea domain under 33 CFR 101.110. Although, it has only recently beginning the dialogue and study of its role and vision for governing the domain. In the *Evergreen II Project Report*, a long-term strategic planning document, Undersea Mission Development is highlighted as a core strategy for the USCG and includes many important considerations [19]. Beyond the regulatory policy over commercial and recreational undersea uses, key drivers include the expanding use of undersea infrastructure with likely environmental and navigational impacts [19]. The increasing nature of unmanned capabilities, quantities, and stakeholders throughout the surface and undersea maritime domains poses several vital questions for USCG leadership in its regulatory capacity.

1.1.3 Organization and Assets Overview

The USCG currently utilizes a network of over 240 cutters, 1,800 boats, and 200 aviation assets to carry out missions throughout the world [3]. These assets are allocated based on strategic mission needs within various areas of responsibility (AOR). Different classes of assets fall under multi-mission shore-based units organized hierarchically (top-down) by Area (national), District (regional), and Sector (large port/harbor) commands. Afloat units are comprised by USCG cutters such as the National Security Cutter (NSC). Sectors are tasked with maintaining a Common Operational Picture (COP) of all assets within their AOR via a central command center. Figure 1.3 shows a high level operational view of the coordinated effort between a Sector command center, cutters and aviation assets to protect U.S. interests throughout its waters and on the high seas [3].

Figure 1.3: USCG Sectors are charged with maintaining a common operational picture throughout their AORs, coordinating various assets and personnel. From [3].

1.1.4 Unmanned Maritime Systems Overview

For the purposes of this work, UMS will be defined as such [15]:

> UMS are defined as unmanned vehicles that displace water at rest and can be categorized into two subcategories: unmanned underwater vehicles (UUV) and unmanned surface vehicles (USV).

Historically, the use of UMS is not new for the U.S. Armed Forces. As far back as World War II, USVs were used for mine sweeping and radioactivity sampling after atomic bomb tests [4]. More recently, the USCG has been using or supervising the use of Remotely Operated Vehicles (ROVs), a type of tethered UUV, for years to inspect, detect, and monitor harbors, oil rigs, pollution hazards and other undersea areas of interest. Industry-operated ROVs played a important role in the cleanup of the devastating Deepwater Horizon spill, and have made recent news for follow-up examinations of the well head [20].

Over the past decade, U.S. Navy has developed master plans separately for USVs and UUVs which have a strong foundation for craft types, vehicle classes, capabilities, and technology needs for military applications. Correlation between a given application for a particular type or class and mission capability areas is not mutually exclusive, which is illustrated by multiple vehicle types and classes for the same USN mission in Figure 1.4. As with any unmanned vehicle, strategic documents emphasize the fact that unmanned vehicle's systems are not entirely unmanned. The idea of the overall system or system of systems (SoS) thinking is critical to analyzing any prospective UMV system.

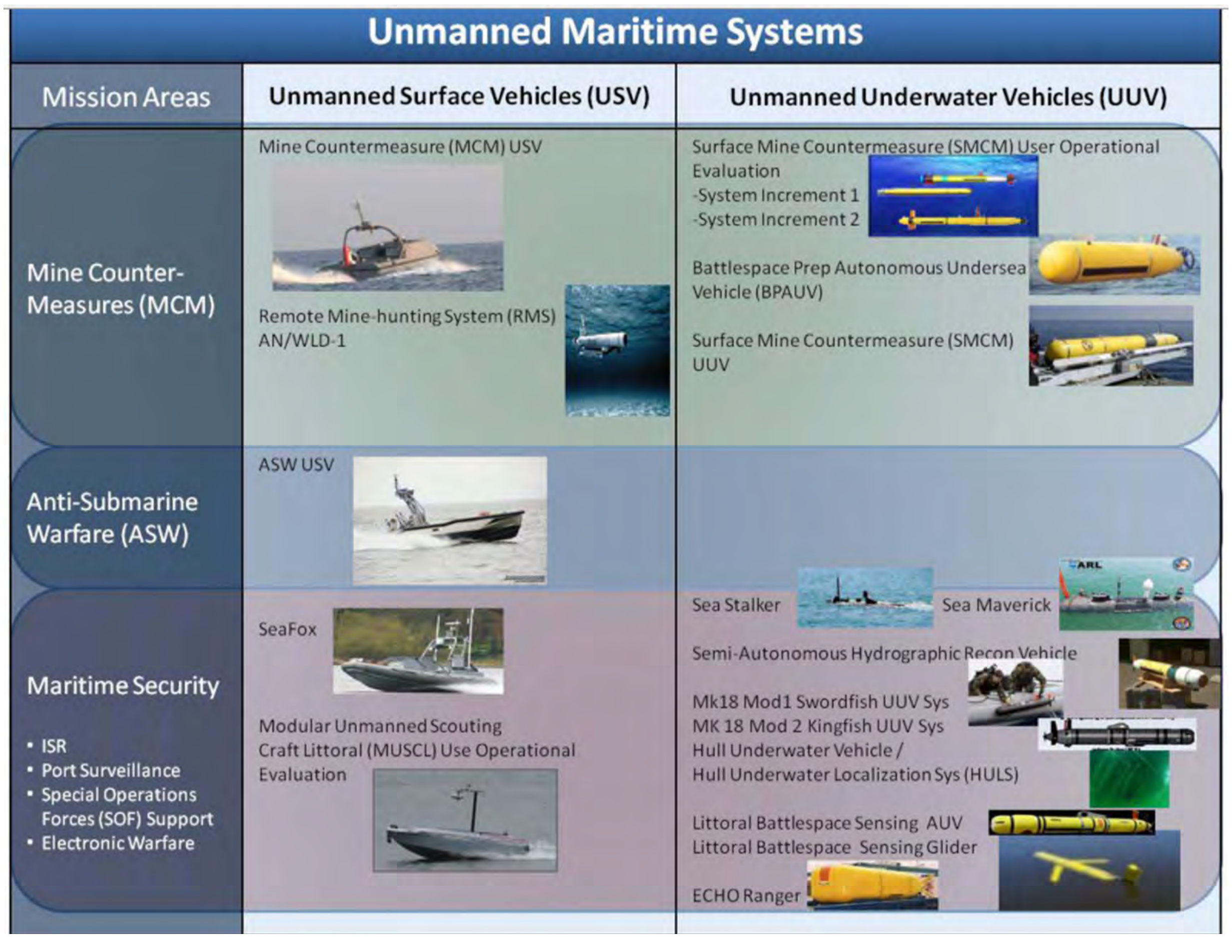

Figure 1.4: USN UMS present many applications for the USCG, especially in the Maritime Security mission area. The variety of vehicles in both size and capability is promising from an affordability perspective. From [4].

In the civilian sector, commercial and academic institutions have designed and developed numerous operational UMS for specific applications such as environmental sampling, hydrography, oceanography, and pipeline survey. As multiple stakeholders develop and design UMS

for a multitude of applications in conjunction with technology advancements, the potential for effective implementable systems grows [4]. Autonomy is an essential capability and challenge for UMS, although current software is at the point in development where moderate levels of autonomy are successful and feasible [21]. Other recent advances in embedded sensing and perception mechanisms promise increased capability performance across the range of applications. As a key area of USCG interest, the undersea faces challenges with regard to communication capabilities. Although UMS present significant technological challenges, an expanding number of applications and users fosters continual improvement.

Benefit and Challenge Overview

The *DOD Unmanned Systems Integrated Roadmap FY2011-2036* highlights the potential for unmanned system to "save lives, reduce human risk, provide persistent surveillance, and reduce operating cost" in addition to also describing some current universal challenges that include Interoperability, Autonomy, Communications, Training, Propulsion and Power, and Manned-Unmanned (MUM) Teaming. That study also addresses current UMS specific limitations such as Endurance, Underwater C2 and Deconfliction, Survivability, Launch and Recovery, and Communication technology for dynamic tasking, querying and data dissemination [4]. These high-level benefits and challenges are representative for USCG UMS and have helped shape the motivation for this work and its findings.

1.2 Motivation

The USCG strategic planning document *Evergreen II Report* highlights three internal core strategies with direct relationships to UMS: Maritime Domain Awareness, Underwater Mission Development, and Intelligent Technology Acquisition [19]. MDA is defined as "the effective understanding of anything associated with the global maritime domain that could impact the security, safety, economy or environment of the United States" [22]. To elaborate on this need, *The National Plan to Achieve Maritime Domain Awareness* outlined several key areas of focus, including the use of emerging technologies [22]. The USCG is also challenged with an aging cutter fleet, some of which will become obsolescent within the next decade [23]. Finally, the USCG does not currently have a strategic vision for UMS rapidly advancing technologies. The areas of emerging threats, strained USCG assets, and UMS technology capabilities are discussed in greater detail in the following sections.

1.2.1 Emerging Threats

The modern world is more dependent on the maritime domain than ever in human history due to the growth of the global maritime supply system. This dependence is compounded by the increasing complexity and use of the EEZ, emergence of transnational threats, increasing scale of catastrophic incidents, and globally by the vastness, anonymity and limited governance of the maritime domain [16]. While some aspects of these threats correlate directly to a particular statutory USCG mission such as Maritime Environmental Protection (MEP), others may be better understood from a regional and/or capability perspective. National strategic studies and headline events have illustrated threats that require or could benefit from UMS capabilities [4]. Geographically, Figure 1.5 illustrates maritime threats and vulnerabilities as depicted in the *2011 DHS White Paper on the U.S. Coast Guard*.

Figure 1.5: The USCG faces increasing threats and vulnerabilities throughout the vast U.S. EEZ. As reliance on the maritime domain increases innovative approaches such as UMS will be vital in gaining awareness, especially in remote locations such as the Arctic. From [3].

Fortunately, UMS have been specifically researched and developed over the past several decades to maturity for near-term USCG applications for the following emerging threat and mission areas:

- Arctic
- Intelligence, Surveillance, and Reconnaissance (ISR) mission threads
- Maritime Security mission including Ports, Waterways, & Coastal Security (PWCS)
- Maritime Environmental Protection

Each of these high-level mission areas are explored in greater detail within the following sections.

Arctic

The Arctic has become one of the most important strategic regions for the nation in recent years and is forecast to increase in significance. Containing 1500 nautical miles of coastline and "an estimated 22 percent of the world's undiscovered oil and natural gas reserves, fish stocks migrating further north, and new access to transportation routes becoming available" [3]. In addition, the Arctic is warming twice as fast as the rest of the globe [24] which is dramatically increasing demand for U.S. strategic capabilities for a variety of military and economic drivers. As accessibility and interest in the region continue to grown, the USCG will be responsible to "preserve freedom of navigation, provide safety of life at sea, protect our natural resources, and preserve the natural environment" [25].

Strategically, The *Cooperative Strategy for 21st Century Seapower* (CS21) provides policy guidance for the USN, USMC, and USCG for core capabilities in the maritime domain, including the Arctic [26]. Similarly, all USCG missions are executed throughout the Arctic region, often with limited or constrained USCG assets. In addition, three aging USCG *Polar* ice-breaking class ships and one National Science Foundation ship are the only U.S. ships capable of polar icebreaking [27]. The large oil reserves in the Arctic have also encouraged increasing oil exploration in the region, which presents potential for maritime pollution. Recent studies such as *Adapting AUVs for Use in Under-Ice Scientific Missions* and *Lightly Tethered Unmanned Underwater Vehicle for Under-Ice Exploration* provide sound scientific foundation for use of UUVs to combat under-ice maritime pollution which is unmatched by most traditional maritime pollution techniques [28], [29].

Intelligence, Surveillance, and Reconnaissance; and Maritime Security

Security and ISR related mission capabilities are some of the strongest motivations for UMS due to the inherently low signature of certain vehicles, such as UUVs, along with the persistent capability of other vehicles, such as *Waveglider* type USVs. As the maritime domain continues to grown in complexity, the vast expanse of un-monitored U.S. EEZ presents a particular

opportunity for persistent UMS to augment and supplement traditional assets. The U.S. Navy has extensively studied maritime security missions for USVs and UUVs applications [30], [13]. These studies provide many proof-of-concept vehicles that are helpful in shaping the analysis of USCG UMS for comparable missions. Additionally, an opportunity to plan for undersea domain awareness via ISR capabilities is inline with USCG internal core strategy [19]. Also, collaborative inter-agency systems are a key driver for maritime security and ISR, but are outside the scope of this work.

Maritime Environmental Protection

In the nation's first declared Spill of National Significance (SONS), the unprecedented *BP Deepwater Horizon* oil disaster clean-up employed a limited use of UMS, specifically Remotely Operated Vehicles [20]. As oil drilling increases throughout the maritime sector, the probability of these types of disasters is higher than ever. Industry UMS and their respective sensors are currently being developed to autonomously navigate and monitor off-shore oil installations and other areas prone to oil pollution [31]. As the lead federal agency for maritime environmental protection, UMS equipped with environmental sampling capabilities would add valuable capabilities.

1.2.2 Asset Obsolescence and Acquisition Strategies

Traditionally the USCG has for better or worse, lived by the saying "do more with less" which recently has become intensified by reduced funding and acquisition pitfalls. As a result of setbacks over the past decade, USCG Commandant Adm. Robert Papp has said that the current CG cutter fleet faces "mass obsolescence." Given cost and schedules associated with new ship acquisition, UMS may present near-term mitigation strategies in conjunction with traditional USCG assets.

In the late 1990s, the Deepwater Acquisition Effort set-out to procure USCG assets in a system of systems approach, by way of optimizing multiple assets within an umbrella acquisition [32]. Unfortunately, by 2007, this program had been heavily criticized due to delays, cost overruns, poor designs, and interoperability concerns that lead to a complete restructuring [32]. These acquisition programs setbacks have effected current mission capabilities by reducing the quantity and type of planned assets, particularly National Security Cutters (NSC) and their respective Unmanned Ariel Vehicles (UAV). The UAVs that were originally designed as part of the system are tremendously delayed in acquisition and are currently still in the planning stages. Due to these delays, a severe Maritime Patrol Hour (MPH) gap of 42% threatens the NSC's overall

mission effectiveness [33].

The age and condition of the *Polar* ice-breaking class ships coupled with the increasing demands for U.S. presence and capability in the region are of concern. Two of the three ships are anticipated to be at there "end-of-service-life" within the next decade with little funding or planned designs for replacements [23].

Understanding that UMS cannot wholly replace the capabilities of a long range UAV or ice-breaking class ship, they could provide a cost-effective system that augments the capabilities. UMS alternatives discussed in this work can maintain or bridge the capability gap for future major assets acquisition.

Recent approaches to system of systems (SoS) analysis and acquisition also promise improvements for future programs. Notably, the use of a System Readiness Level as a combination of Technology Readiness Levels and Integration Readiness Levels promises to reduce or more precisely account for risk, especially in new technology acquisitions such as UMS [14].

1.2.3 Rationale for Domain-neutral USCG UMS analysis

Throughout this work, USCG UMS is analyzed in a holistic systems approach. This approach focuses heavily on effective needs in the preliminary stages, but does not imply a specific solution or domain (i.e. underwater or surface). Learning from the U.S. Navy's USV, UUV master plans and subsequent recommendations found in *A Survey of Missions for Unmanned Undersea Vehicles*; a comprehensive mission driven systems analysis of UMS is more beneficial than specific vehicle or domain analyses [34]. This helps streamline and reinforce the top-down mission needs process along with the service's vision for internal analysis (i.e. planning documents) and external stakeholders (i.e. commercial designers and manufacturers).

1.3 Contributions

This work provides a thorough analysis of UMS from the systems engineering prospective to inform USCG decision makers of capability-added near to mid-term feasibility through a notional timeline for system acquisition. Beginning with a USCG needs analysis that is correlated to current and future UMS applications. It provides the foundation for USCG UMS capabilities analysis through the drafting of several concepts of operations such as aids to navigation and maritime security mission packages. From the series of mission packages developed and detailed based around necessary capabilities, commonalities are identified and assessed. Platforms

were selected that relate the commonalities between mission packages to evaluate the feasibility of three multi-mission USCG UMS alternatives. The three notional UMS alternatives are discussed in relation to key system enablers of technology, capability, policy, and supportability and manpower. Finally, a notional timeline for system acquisition is presented for each alternative based upon the earliest possible key system enabler.

1.4 Research Questions

This work uses a systems approach to focus on the application of UMV for USCG use in the near to mid-term, within five to ten years. To account for the multi-mission nature of the service and multi-dimensional threats within maritime domain, this work identifies specific capabilities necessary to effectively address those needs. The analysis also provides insight into the importance of system considerations that will ultimately affect any UMS program's performance such as command and control, manpower, and policy.

The maritime domain and unmanned technologies are important for an ever-growing number of stakeholders in a variety of sectors and also justifiably lend themselves to joint and inter-agency initiatives. Noting those valid reasons for a national UMS master plan or analysis, this work will focus solely on USCG applications. This is because USCG UMS applications are diverse enough to warrant service-specific analysis, and acquisition of such vehicles is also service-specific.

The speed of technology improvements has showcased the need to plan for future capabilities now. A "wait and see" approach [35] and lack of a strategic vision for UMS will likely leave the USCG at a disadvantage risking reduced effectiveness and affordability missteps. That being said, assumptions about new technologies is uncertainty and investigative analysis is only the first step in the procurement life cycle.

The scope of this work is focused on USCG missions and unmanned maritime technologies to add motivation for a more comprehensive master plan or roadmap for their acquisition and implementation. The following research questions are intended to help guide this work and provide a framework to understand the conclusions and recommendations:

- How can the USCG utilize unmanned systems to enhance capabilities across multiple missions?
- What USCG missions are best suited for unmanned technologies/platforms?
- Which Concepts of Operations(CONOPS) will best correlate to proposed unmanned sys-

tems in the near to mid-term?
- Which key system enablers are most significant to the implementation of UMS?
- What is a feasible timeline for UMS Acquisition?

A comprehensive UMS is extremely complex and this work cannot possibly investigate all facets. Most primary considerations are included, at least from an acknowledgement perspective, but may not be fully developed. Some select technologies have enabled UMS to be usable for given USCG applications, but their specific design is outside the focus of this study as well. This work's research questions help frame a justification for USCG UMS acquisition through further system development and design.

1.5 Organization of Thesis

Chapter 1 provided background information about the U.S. Coast Guard including missions, jurisdiction, and organizational structure and assets. This chapter also reviewed the current application of Unmanned Maritime Systems for both military and civilian applications. It also highlighted the primary motivations for the thesis, contributions, and the scope of its breadth in the research questions.

Chapter 2 presents the systems engineering process and methodology for this work, including a capabilities analysis. USCG unmanned maritime system capabilities are discussed and relatively ranked against a representative set of mission packages developed from the proposed concepts of operations (CONOPS). Commonalities among mission packages are then observed to identify which CONOPS can be fulfilled by multi-mission UMS alternatives.

Chapter 3 develops three multi-mission USCG UMS alternatives: Cutter-Based Tactical UUV, Shore-Based Coastal UMV, and Strategic Offshore USV. These alternatives are discussed and analyzed with regard to vehicle and system characteristics, including representative commercial examples. Using these alternatives as a framework, USCG UMS functional and physical system architectures are developed to further decompose the system.

Chapter 4 gives an overall system feasibility analysis. Near- to mid-term considerations drawn from unmanned system roadmaps for comparable systems, maritime threat forecasts, and the alternatives' key system enablers; including technology, capability, policy, and supportability and manpower. Associated risk and mitigation strategies are discussed, which help inform the developed timeline for USCG UMS feasibility.

Chapter 5 provides a summary of findings and areas for future research with regard to this work. Recommendations are made based on the findings and analysis, with the goal of encouraging a holistic USCG UMS vision and eventual implementation in the near term. Finally, conclusions are drawn about the application of UMS for USCG missions.

CHAPTER 2:
Conceptual Phase Systems Engineering Analysis

2.1 Systems Engineering Process

To provide a meaningful frame of reference for this analysis, an adaption of the classic waterfall systems engineering (SE) process model was utilized. This waterfall process model was originally introduced by Royce in 1970 and has become one of the industry standards, with many strong parallels to the USCG acquisition process, vital to any real-world implementation of proposed systems [5]. SE process model methodology provides a logical and traceable flow of information between the different phases, although iteration is to be expected within and between phases. Sequential documentation provides the basis for verification and validation of final system design recommendations. Figure 2.1 visually shows the nested waterfall SE process model that is used in this work.

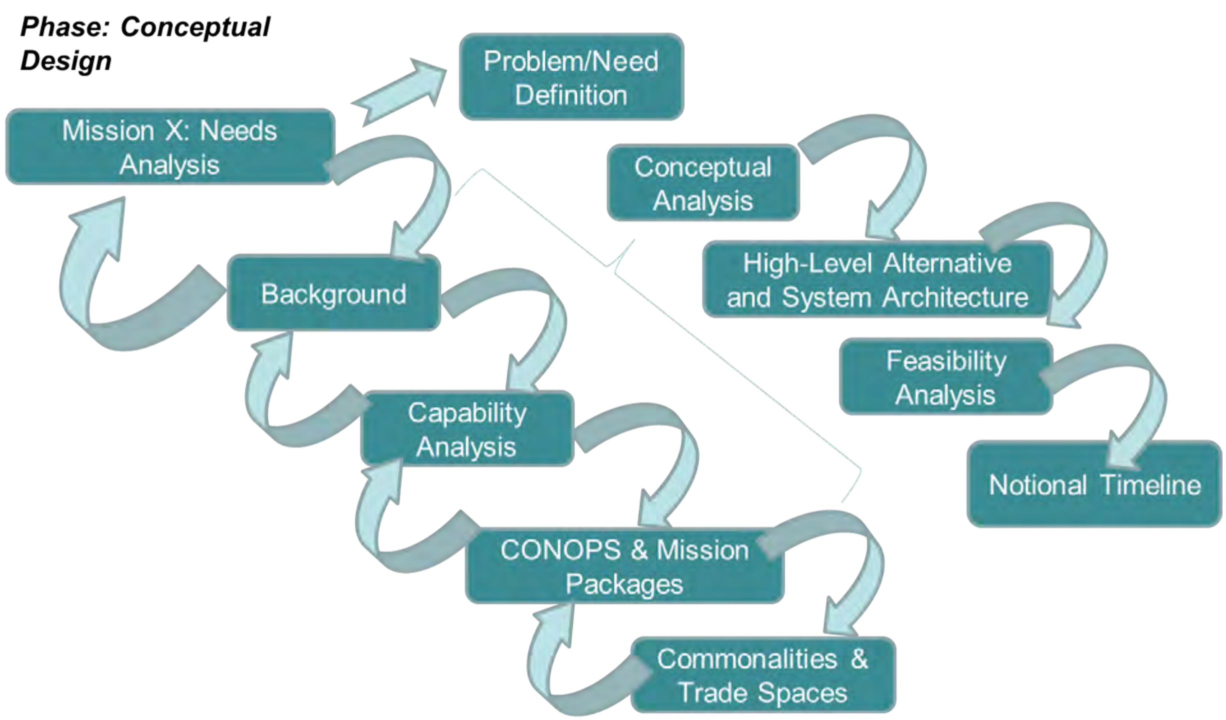

Figure 2.1: This tailored SE process model depicts the methodology for this work's analysis. Each step within the conceptual phase feeds the next and vice versa through the iterative nature of research and analysis. After [5].

Due to the scope of the material and the diverse mission needs of the USCG, a nested approach

provides iterations of the waterfall process for each set of mission packages. The bulk of this nested process focuses on capabilities analysis supported by a recent RAND publication titled "Portfolio-Analysis Methods for Assessing Capability Options." [36] This work stresses the mission driven top-down approach to needs analysis, but also incorporates a bottom up approach to evaluate UMS options. Chapter 1 provides the the bulk of information regarding high-level needs and background analysis for the motivation of UMS analysis, the subsequent stages are discussed throughout the remainder of this work.

It is important to note that the analysis in this thesis is primarily based in the conceptual design phase. Conceptual design and effective problem/needs analysis, also known as "front-end" work, has been shown to be a critical step in any SE process and can have significant impacts on later phases, making its analysis and assumptions key to system success. Design oriented SE stages such as test and evaluation are not addressed in this work because USCG UMS is too premature for effective analysis.

2.2 Concept of Operations (CONOPS)

The CONOPS provides a context for UMS in various USCG applications. In describing the scenarios, characteristics, and interactions of the potential UMS, the CONOPS communicates to stakeholders a high-level operational and systems view. Through the CONOPS, understanding of UMS system priorities, movements, and relationships helps relate to current mission needs and gaps providing value-added material solutions. The CONOPS are further categorized into mission packages. These mission packages are not an all inclusive set of mission packages nor are they evaluated for optimal effectiveness. They represent a set of test cases for a range of possible situations from a flexibility, adaptiveness, and robustness (FARness) perspective [36]. The CONOPS also allows UMS technology to be analyzed quantitatively while reserving explicit technical specifications and metrics for future, likely more appropriate, requirements.

2.2.1 Mission Package Capability Factors

In this section, capability factors are defined with respect to UMS. Each specific factor comprises many attributes, which are described below for clarity. Inherent nuances between CONOPS do make comparison of some factors less distinct, which is further discussed in Chapter 3's derived UMS alternatives section. Capability factors are rated from (1, red) low to (5, green) high based on their relative ranking compared to the other CONOPS, and are summarized at the end of this chapter.

Many of capability factors represent meaningful tradespaces that impact the feasibility timeline found in Chapter 4. For instance, the trades between Command and Control(C2) and Autonomy is important for all UMS and will likely change with advances in autonomy technologies. As communication, within the C2 capability factor, capabilities are reduced the need for autonomy is increased or alternatively, as technology allows for more autonomy the demand for communication is reduced [13].

Figure 2.2 outlines the capability factors and their associated high-level attributes.

Figure 2.2: This taxonomy of capability factors describes the characteristics of mission packages and their needs. The capability factors with the most commonality across mission packages provide input for UMS alternative's domain and characteristics.

Persistence: Often described as a major potential advantage of unmanned systems over manned systems with two key attributes: Endurance and Seakeeping. Endurance refers to the system's ability to sustain prolonged periods of time in operation, with correlations to system suitability measures of reliability and maintainability. Seakeeping is in part the vehicle's seaworthiness (i.e., stability, depth rating (for UUV)) and propulsion characteristics (i.e., fuel utilization, propulsor) and to a lesser degree durability and survivability.

Coverage Area: As one of the most significant operational factors, this factor comprises vehicle speed and range. Range of the vehicle is heavily dependent on the UMS launch and recovery mechanism, and therefore highly dependent on UMS design. The speed attribute can be fur-

ther broken down into its characteristics of cruise speed, maximum speed, and related energy requirements with associated duration.

This factor is also closely influenced by persistence, perception, and timeliness, but mission requirements provide clear delineations for inclusion of this factor separately.

Timeliness: This factor is seen as how quickly a UMS can reach its destination and carry out its given mission from initiation to engagement, excluding logistics for initial stationing. In other words, it is the time from "launch" or direction to effective operation most closely related to speed versus distance required for a given mission package.

Perception and Prosecution: This factor is heavily related to the UMS's ability to carry out surveillance, detection, classification, and identification through sensing. Due to the diverse nature of mission packages, there is large variability in the type of sensing and degree of complexity. Other related attributes are the perception factor's energy requirements, size, weight, processing time, fidelity, and reliability.

While the majority of the mission packages require perception functions with prosecution action occurring as a follow-on from manned assets, prosecution is a potentially useful component of UMS. Mission packages requiring types of weaponized payload or other deterrent capabilities would be included within this factor.

Command and Control: This factor is related to the UMS's ability to communicate and operate the vehicle. Communication is a key attribute for all UMS with associated attributes as data rate, processing capability, range, detectability, along with interoperability of information gathered [15]. Tenets of common definitions for interoperability include system functionality descriptions and architectures, messaging standard, and data models [4]. To operate the UMS, human system integration (HSI) considerations such as Manned-Unmanned Teaming (MUT) are also included in this factor [13].

Autonomy: This factor has numerous facets which are beyond the scope of this work, but broadly it is seen as the degree to which the vehicle can carry out its task with regards to human input. More precisely, the *Defense Science Board (DSB) Task Force Report on the Role of Autonomy in DoD Systems* defines autonomy as a capability or set of capabilities that enables a particular action of a system to be automatic or, within programmed boundaries, self-governing, under the supervision of a human operator [21]. Degrees of autonomy also incorporate the complexity of that autonomy, where an unmanned buoy that simply stays on-station via GPS

would rank lower than a security escort that is required to navigate in a network and follow some form of navigation rules with limited human involvement.

Environment Integration: Environment integration is seen as the degree to which the UMS is observed and interacts with others in its area of responsibility. On opposite sides, ISR-type applications seek a very low signature whereas aids to navigation type applications require a substantial amount of observables and communication with vessels. Attributes such as signature(s), observables, and non-operator communication are included.

The following mission packages, with varying degrees of complexity and feasibility, are discussed in greater detail in the subsequent sections:

- Aids to Navigation
  - Buoy Augment
  - Temporary Aids to Navigation
  - Disaster Relief
- Maritime Security
  - Over-the-Horizon Maritime Domain Awareness (MDA)
  - Port Security, Anti-Terrorism Harbor Patrols and Remote Location
  - Security Escort
- Living Marine Resources
- Maritime Environmental Protection
  - Oil in Ice
- Search and Rescue
- Marine Safety

Mission packages are described through plausible but hypothetical scenarios to hypothesize applications and considerations for UMS for each. Capabilities factors are ranked relative to other mission packages from (1)low to (5)high based on the scenario and background information for a given mission package. Capability comparisons and analysis is provided in greater detail in later sections.

2.2.2 Aids to Navigation (ATON)

The USCG is responsible for the administration and operation of the U.S. Aids to Navigation system, which is used throughout U.S. waters as crucial infrastructure for safe and efficient military, commercial, and public navigation by way of navigational devices within visual, audio,

and radar range of the mariner [37]. For fiscal year 2012, the enacted budget authority for USCG ATON missions was 23 percent of the total USCG budget by mission [38].

Many forms of traditional navigation are being replaced or augmented by electronic means, such as the conversion to electronic navigation charts, Automatic Identification System (AIS), Differential Global Positioning System (D)GPS, and the collective integrated bridge system (IBS). These modern forms of navigation and their corresponding international and domestic regulatory requirements are drastically increasing navigation capabilities which, in turn, could decrease the need for traditional ATON system elements. Noting the fiscal and logistics demand of current ATON systems, an opportunity exists to maintain or improve the level of navigation safety through current e-navigation devices and the use of UMS for certain ATON mission areas. Figure 2.3 shows a conceptual graphic of the size and plausible configuration of a USV for self-positioning that could be adapted for ATON applications.

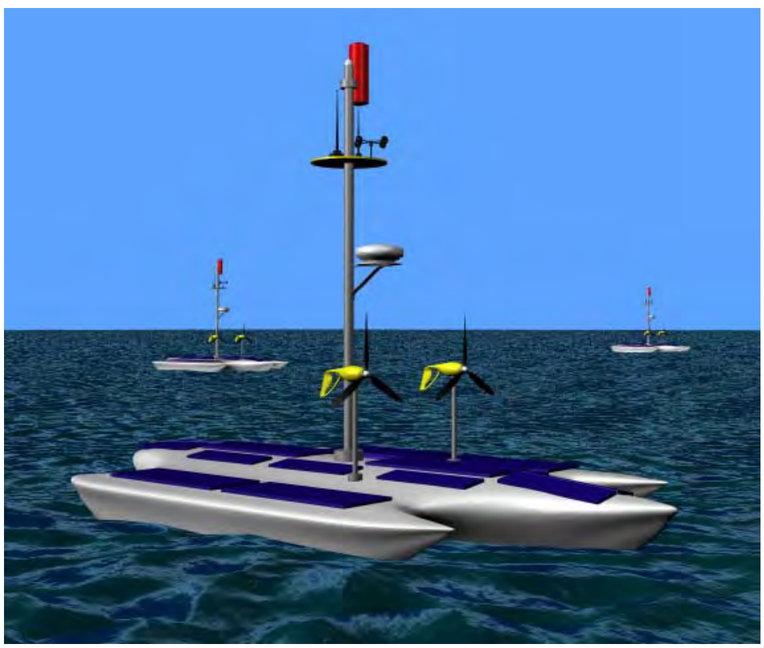

Figure 2.3: The ASC Sea Rover concept vehicle depicts a UMS designed specially for ATON missions. Many operational concepts involve the augmentation of traditionally moored buoys with “smart” UMS buoys that could send navigation information as well as receive and relay maritime domain awareness information. From [6].

Buoy Augmentation Key station-keeping ATON system elements are moored buoys and RACONs (radar beacon transponders), both can be functionally replicated by comparable-sized USVs. Recent studies have analyzed a “Self-Positioning Smart Buoys” which is approximately recreational-kayak sized outfitted with similar components as a moored buoy and capable of providing a per-

sistence capability of month(s) [6]. Similar USVs showcase high seakeeping in even the roughest seas although station-keeping is typically degraded in higher seas. Other station-keeping techniques such as the use of a sea anchor may provide a healthy balance between higher energy intensive components for transit propulsion, and lower energy components for station-keeping. A necessary configuration, in terms of quantity and spacing, of self-positioning USV(s) ATON would be heavily dependent on the navigable waterways characteristics and traffic needs, much like traditional ATON [37]. Preliminary sensors would include (D)GPS, AIS, a radar transponder (as similar to RACON as possible), satellite communications link, and appropriate ATON lighting/signals.

Temporary Aids to Navigation Alternatively, beyond augmentation of traditional station-keeping ATON, the maritime domain in multiple constantly changing scenarios requires flexible and timely response with ATON. For example, the USCG's role in establishing safety and security zones around hazards to navigation and other maritime areas of interest is often time and resource intensive, especially in remote locations.

Disaster Relief In addition, for maritime disaster relief, the USCG authorities such as Federal On-Scene Coordinator, Captain of the Port, and others, provide a strong motivation for unmanned harbor patrols and situational awareness gained through additional sensors on UMS of this variety. Instead of USCG stations deploying small boat(s) or other assets to inform the public, monitor an area, or enforce applicable laws, USVs could be deployed quickly via land, water, or air (depending on their size) and provide extended persistence over manned assets [39]. The timeliness of response would be dependent on the particular need, but the ability for the USV to be capable of persistent station-keeping, enhanced sensors/transmitters (radar beacons), and the dynamic re-positioning to adapt to the changing maritime environment (such as a large pollution spills or security zone that move with the current). Once the USV are established for a particular security zone, sensors would feed the USCG Sector with targeted maritime domain awareness information vital to providing decision makers, such as the Sector Commander, a more robust common operating picture. Additional sensors packages could include acoustic sensor for towed array undersea detection, radar, high definition cameras, fluorometer, and oceanographic instruments.

The USV's payload (sensor) and propulsion power demands could be met through an increasing number of mechanisms. Leveraging COTS USV's power supplies, a combination of wave-power (station keeping), solar-power (for sensors), and external recharging (for persistence

or during heavy weather/low solar) have been shown to be effective in the maritime environment [40]. External recharging could be accomplished by the use of an autonomous docking station, housed by a traditionally moored buoy or similar device and could also act as central location for launch, recovery, and maintenance. Logistically, the launch or recovery of such USVs would require significantly less resources than current ATON.

Notwithstanding other plausible mission modifications or payloads for this proposed UMS, this type of system would require a number of human operators varying with complexity of the system. Smaller type systems with one safety/security zone, hazard to navigation, or fairly constant small coastal region could likely be monitored by one person with a medium demand for communications from a Sector Command Center, Vehicle Traffic Scheme (VTS), or even a smaller USCG station. Launch and recovery of such a USV could be launched from the shore or from the a small boat, buoy tender, or air platform.

Capability Factors

Persistence: For buoy augmentation, comparable to a fixed ATON, the highest available persistence is desired, at a minimum of months. For temporary ATON, the ability to dynamically reposition and maintain on-station for a moderate duration (days to weeks).

Coverage Area: This factor is low due to the stationary nature of ATON. Although temporary ATON may require low-moderate and disaster relief would require moderate due to the situation they are responding to. The latter two do not require more coverage because they will be for a short duration in coastal waters as defined in the CONOP.

Timeliness: This factor is low because buoy augmentation would not require a buoy to respond, but temporary ATON and disaster relief mission packages require moderate speed moderate range, thus a moderate ranking.

Command and Control: To fully utilize the benefits of an ATON UMS, dynamic repositioning would add valuable range and flexibility without the time and expense of manned transportation. To achieve these features a combination of moderate communications for relay of waypoints, propulsion for repositioning, and autonomy are necessary. Typical VHF ranges would be practicable, but for more remote, off-shore, or higher fidelity information sharing, a satellite communications link is necessary.

Due the the semi-stationary nature and commonality with fixed ATON, Usability and human system integration (HSI) issues from an operation and maintenance perspective rank relatively

low, although the ability for mariners to recognize and fully use these aids will require revision to regulations and current practices, including navigational charts, and training. Key operational factors include launch and recovery, maintenance, and system monitoring.

Perception and Prosecution: Though these platforms could be used to great affect with perception sensors for additional environmental, ISR, and MDA functions, the ATON mission packages require a low ranking. Disaster relief would require moderate perception such as high-definition cameras to provide situational awareness.

Autonomy: The accuracy of ATON is an essential function for their mission. Although fixed aids are required to be positioned a higher degree than floating aids, to augment the fixed aid with a UMS would require comparably high levels as defined in ”National Geodetic Survey.” [37]. This is approximately within meters, at the most, and would require propulsion and seakeeping compatible with both the current and weather for a given area. Though vital and almost fully autonomous, the degree of complexity for station-keeping autonomy is fairly low. Temporary ATON and disaster relief require surface navigation which adds considerable complexity and moderate autonomy.

Environmental Integration: This is a key factor for the ATON CONOPS because their primarily function is by way of communication to the mariner. Utilizing transponders will be essential to provide a meaningful signature to communicate location to the mariner. Visual dayshapes and markings are necessary in accordance with the ATON Manual [37], but visual observables will likely be reduced in comparison to fixed ATON.

Table 2.1 shows the relative rankings for this section, as discussed more completely in the capabilities summary section. Using a Likert scale from 1 as low (red) to 5 as high (green) mission package capability needs are relatively ranked against each other, based on the CONOPS capability factors discussed throughout this chapter.

2.2.3 Maritime Security

Maritime Security (MS) is a national strategic concern with direct correlations to several USCG missions. USCG MS missions are: Ports, Waterways, and Coastal Security; Migrant Interdiction; Drug Interdiction; and Defense Readiness. These missions are often conducted in the joint maritime environment and UMS CONOPS for these missions have a strong correlation with USN UUV/USV master plans [30] [13]. Many key capabilities have been designed into currently operational USV/UUV focused around MS, making this mission package fundamental

Mission Packages	Persistence	Coverage Area	Timeliness	Command and Control	Perception and Prosecution	Autonomy	Environment Integration
Buoy Augmentation	5	1	1	2	1	1	5
Temporary Aids to Navigation	3	2	3	3	2	3	5
Diaster Relief	3	3	3	4	3	4	4

Table 2.1: The capability factor rankings highlight high demands for persistence and environmental integration, with low coverage area and perception requirements.

for UMS, in addition to enabling other subsequent missions [13].

In *A Cooperative National Strategy for 21st Century Seapower*, a collaborative strategy for USCG, USN and USMC, states "the creation and maintenance of security at sea is essential to mitigating threats short of war, including piracy, terrorism, weapons proliferation, drug trafficking, and other illicit activities." [26] A critical element of MS for all three stakeholders is persistent ISR, but practically UMS of almost every variety provide some level of ISR, making other factors more influential when considering MS CONOPS [13]. Interoperability within this context is critical to leveraging all available capabilities in the joint maritime environment, especially due to the extensive research and development of UMS in the U.S. Navy. Noting interoperability's importance, this MS CONOPS will focus on USCG UMS applications to capture a user oriented perspective for undersea and surface MS.

USCG UMS Maritime Secuirty missions threads include:

- Over-the-Horizon Maritime Domain Awareness
- Anti-Terrorism Harbor Patrols and Remote location monitoring
- Security Escort

Each of these mission threads are described in greater detail in the sections that follow.

Over-the-Horizon Maritime Domain Awareness

Consider the following hypothetical scenario: A UUV is launched from a surface ship, such as the National Security Cutter (NSC), Fast Response Cutter (FRC), or forthcoming Offshore Patrol Cutter (OPC), to extend the ship's ISR capability. The UUV, which has an inherently lower signature than a USV, tactically searches a critical area with passive acoustic sensors

for detection of vessels illegally operating such as a Self-Propelled Semi-Submersible (SPSS) carrying illegal drugs. Following detection, classification and localization, the UMS relays the target information in near-real time when surfaced for cutter persecution. Once the search and mission are complete, the UUV receives new commands and returns for recovery on board the cutter or ashore.

Other configurations of one or more UUV are used to establish over-the-horizon offshore nodal networks to patrol vast but critical areas for fishery zone enforcement and Living Marine Resource violations.

This UUV would have limited communication ability while submerged but could accommodate rerouting when surfaced, in addition to having weeks to months of endurance, allowing the cutter to conduct other operations with little Command and Control necessary unless notified.

Over-the-horizon maritime domain awareness is also an enabling form of ISR that relates to the vast majority of USCG and other US maritime missions.

Port Security, Anti-Terrorism Harbor Patrols and Remote Location

Consider the following hypothetical scenario: A small UUV is deployed from a USCG station in a large port where there are several different forms of critical infrastructure such as bridges and manufacturing plants. Instead of the mandated small boat doing routine checks of the harbor requiring manpower, time, and additional fuel costs, the UUV follows given waypoints. It autonomously surfaces at set locations and assess infrastructure via a high definition camera, communicates anomalies back to the station or local sector command center and continues it mission unless rerouted.

Alternatively, there are reports of explosives or chemical, biological, radiological, and nuclear defense (CBRN) threats at critical locations throughout the harbor. These reports are expeditiously investigated by a team of UUV/USVs capable of "rapidly producing fine resolution, shallow-water bathymetry maps using a multibeam sonar, detecting chemical threats using an on-board mass spectrometer and monitoring oceanographic parameters using off-the-shelf instruments." [39]

In a more remote coastal area, there is intelligence that historic undersea gravesites of significance are being looted for their artifacts. The USCG deploys a "Bell Ringer" type UUV to act as an undersea barrier equipped with acoustic sensors to detect and identify intruders. Once looters reach a threshold alarm water depth, the UUV surfaces, collects additional intelligence,

and alerts the sector command center for enforcement.

Security Escort

Consider the following hypothetical scenario: A naval submarine is underway and making way in an outbound transit of the Sector Seattle Captain of the Port Zone with a force protection USCG USV escorting it and enforcing the 1000 yard security zone as per 33CFR165.1327 [41]. This USV is launched from the station and operated remotely from the sector command center. It carries a force protection suite with lethal and non-lethal payloads, in addition to a loud speaker for deterrence. The USV is approximately the size and payload of the RAFAEL Protector 9m, or USN Harbor Class (7m).

Capability Factors

Persistence: Persistence for OTH MDA and remote location mission packages is high due to long endurance requirements. Security escort and port security mission packages are regarded as low-moderate and moderate respectively because the CONOPS call for a limited endurance for coastal missions.

Coverage Area: Similar to persistence, OTH MDA and remote location require high ratings for this factor to enable offshore and isolated locations with long transit times. Although port security and security escort mission packages are coastal, their coverage area is moderate because they are required to navigate throughout sizable large harbors and inland waterways.

Timeliness: Remote location receives a low rating because it is effectively an underwater bell ringer, but security escort is seen as having a high need for speed to maintain cruising speed with submarines and respond to security zone threats. OTH MDA and port security require moderate timeliness because speed is important for their missions but not as critical compared to other mission packages.

Command and Control: Moderate-high ratings are required for OTH MDA, port security, and security escort because their mission require real-time communications and tasking. Remote location is low due to its relatively infrequent communication and re-tasking.

Perception and Prosecution: Perception is a moderate high capability factor for OTH MDA, port security, and remote location because they rely on sensors that are capable of identifying and classifying a threat. Security escort is the only mission package with a prosecution element (i.e., weapons or deterrent payload) although it also receives a moderate-high rating for this factor.

Autonomy: The security escort mission package requires the most complex degree of autonomy to sense, avoid, and engage hostile contacts. The other mission packages require low-moderate (for undersea domain applications) and moderate (for surface domain applications) degrees of autonomy with some complexity for navigation.

Environmental Integration: Security escort also requires a high level of environmental integration because the CONOPS relies on its ability to be observable within the environment. Remote location has a low rating because of its isolated area of responsibility. OTH MDA is seen as moderate-high because of the desire for low ISR capabilities for MDA applications.

Table 2.2 shows the relative rankings for this section, as discussed more completely in the capabilities summary section.

Mission Packages / *Capability Factors*	Persistence	Coverage Area	Timeliness	Command and Control	Perception and Prosection	Autonomy	Environment Integration
OTH MDA	4	5	3	4	4	2	4
Port Security	3	3	3	4	4	3	3
Remote Location	5	4	1	2	4	2	1
Security Escort	2	3	5	4	4	5	5

Table 2.2: The capability factor rankings highlight the high requirements for security escort autonomy, environmental integration, and timeliness.

2.2.4 Living Marine Resources

In the Northwestern Hawaiian Islands, one of the most isolated US EEZs, the Papahānaumokuākea Marine National Monument (established in 2006) is the largest conservation area under the US flag [7]. This area faces several threats to protecting and preserving its unique natural habitat and indigenous species including maritime pollution, climate change, over fishing, and alien species [7]. Figure 2.4 shows the vast expanse of the island chain including the EEZ and monument delineation markings.

In the near future, existing licenses for commercial bottomfishing will expire and the area will not legally be used for fishing purposes at all using current forecasts. Consider a hypothetical scenario where a fleet of foreign commercial fishing ships intends to ignore these new regulations, with the understanding that the remote area will have little to no government oversight.

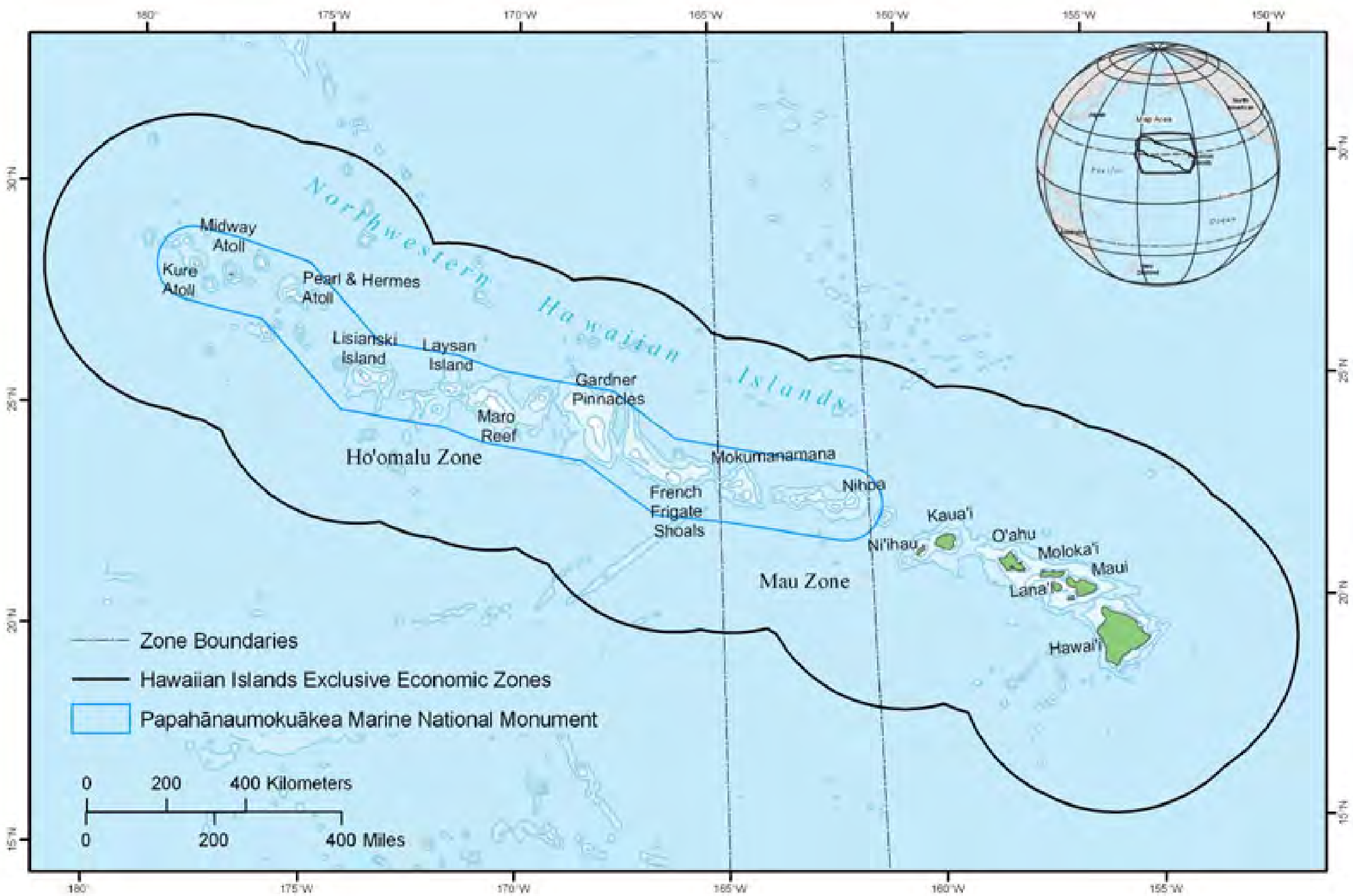

Figure 2.4: The Northwestern Hawaiian Islands were designated as a marine national monument in 2006 and encompasses 139,797 square miles. From [7].

The USCG, in tandem with NOAA and the State of Hawaii, launch via shore or USCG/NOAA ship a series of high persistence USV to autonomously transit to the critical bottomfishing areas within the monument. Ship detection sensors would be critical to this mission, along with standard navigation sensors such as GPS and AIS in addition to cameras and satellite communications equipment. Due to the environment's rich scientific significance, additional scientific sensors could enhance the efficiency of this UMS. Allowing USVs to monitor the area until encroachment occurs, reducing the capabilities gap for the USCG's highest fisheries priority of "Protecting the U.S. Exclusive Economic Zone from foreign encroachment." [42]

Capability Factors
Persistence: This mission requires a high level of persistence due to the long endurance needed to transverse the isolated offshore island chain.

Coverage Area: Requires a high level for the same reasons as persistence.

Timeliness: The CONOPS was intended with a low timeliness requirement. Pre-positioning UMS in locations susceptable to living marine resource violations is a key assumption that lead to the low timeliness rating.

Command and Control: Low-moderate command and control because the majority of operations are self-suficent until the sensing threshold is met or retasking is necessary.

Perception and Prosecution:Perception is moderate to high to give the best chances of identifing infractions. This CONOPS could easily be modified to resemble similar attributes as the remote location mission package.

Autonomy: Simplistic waypoint following and minimal navigation risks inform a low-moderate rating.

Environmental Integration: Similar to the remote location mission package, a low rating is needed to facilitate its mission in the Northwestern Hawaiian islands.

This subsection's capability factor rankings are shown in the overall capability factor ranking summary seen in table 2.3.

2.2.5 Maritime Environmental Protection

The Polar regions have seen a dramatic increase in oil exploration and drilling, and will likely see an increase in commercial maritime commerce in the near future due to the receding Arctic

ice [24]. While the demand for USCG assets and capabilities grow in the Arctic, the effectiveness of certain missions is naturally threatened by the harsh and unique climate. A substantial USCG and industry challenge in the Arctic is the threat of oil pollution in icy waters. Most conventional response assets have a limited capability to detect and clean up oil pollution in icy waters, but recent UUV technologies show promising capabilities in these situations [29].

Consider the following hypothetical scenario: An oil rig suffers a catastrophic failure and oil begins to drift into the nearby ice, mostly concentrating underneath the ice sheet. The UMS utilizes a team of man portable, with 40+km range to detect the oil boundary with a multi-beam sonar [29] from beneath meters thick ice. At that depth, clean up options are severely limited, so the UUV releases dispersants to mitigate some of the pollutant's damage.

Capability Factors

Persistence: Moderate persistence would be required because of the seakeeping demands in the harsh environment, although this mission package requires relatively low-moderate endurance.

Coverage Area: The coverage area is moderate-high because of the uncertainty of oil localization. Also, these assets would probably not be pre-positioned so a large search area is possible.

Timeliness: Moderate timeliness is necessary to search a larger area.

Command and Control: Real-time updates for manned intervention are necessary even though searching may be simplistic in design, resulting in a moderate rating.

Perception and Prosecution: This is a the highest relative rating across all mission packages for perception because of the delicate nature of environmental perception, and the desire to obtain a sample with legal rigidity which could enable future law enforcement options.

Autonomy: Moderate level of autonomy is aligned with a assumed simplistic search pattern for oil and environmental pollutants.

Environmental Integration: Low-moderate environmental integration because there are few signature needs.

This subsection's capability factor rankings are shown in the overall capability factor ranking summary seen in table 2.3.

2.2.6 Search and Rescue

Search and Rescue (SAR) is one of the USCG's oldest missions dating back to the U.S. Life-Saving Service [1]. Every day, USCG men and women put themselves at risk to save lives in even the harshest climates. While this is one of the most traditional and noble USCG undertakings, reducing the risk and improving the safety of the personnel is a key benefit of unmanned technology. Innovative applications of UMS could provide additional SAR capability while mitigating or eliminating risk to the USCG members.

Consider the following hypothetical scenario: In very heavy weather, a commercial fishing vessel reports a "Mayday" call over channel 16 to the local sector command center from roughly 40NM offshore. The vessel's master activates his Emergency Position Indicating Radio Beacon (EPIRB) and Search and Rescue Transponder (SART) which transmits his location to 9GHz X-Band radar within range. USCG helicopters and smallboats are deployed but the sea and wind conditions quickly worsen beyond the limitations of the airframe and hull. A USCG Offshore Patrol Cutter is currently underway in the area but also cannot deploy their smallboat for weather concerns. The OPC deploys a heavy weather USV/UUV equipped with radar to locate the SART and deploy an inflatable liferaft until the weather subsides and additional assistance can arrive.

Capability Factors

Persistence: SAR missions require moderate-high persistence because their application would be in heavy sea-states requiring significant seakeeping. Endurance may also be high, especially in cases where UMS are uniquely suited to stay on-station for prolonged periods of time.

Coverage Area: Moderate-High coverage area because the SAR mission is not limited to coastal areas.

Timeliness: High timeliness in terms of maximum speed to quickly respond in locating a SAR victim.

Command and Control: Moderate command and control because this CONOPS relied on the use of autonomy and perception to direct the UMS.

Perception and Prosecution: Moderate perception because the technologies to identify a SART are mature.

Autonomy: Moderate autonomy for searching although this CONOPS does assume an isolated

area in rough seas where other risks of collision are reduced.

Environmental Integration: Low rating because ISR signature and observables are not essential to this CONOPS.

This subsection's capability factor rankings are shown in the overall capability factor ranking summary seen in table 2.3.

2.2.7 Marine Safety

One of the key objectives of the USCG marine safety mission is to promote safety and security on all U.S. flagged and foreign-flagged commercial vessels in U.S. waters through a coordinated effort with industry partners, primarily through inspections and investigations. While inspections typically occur at fairly consistent intervals, most investigations are initiated by a reportable marine casualty, such as a collision or grounding, as defined by 46CFR4 [43]. While mariners are legally required to report such casualties to the nearest USCG unit, oversight of the situation and time-sensitive investigation relies heavily on external reporting.

USCG UMS that enhance maritime domain awareness for other missions threads, such as aides to navigation or maritime security, should be designed to be cognizant of reporting marine casualties to assist notification. Additional sensors may aid the ability to detect these casualties such as fluorometers for oil pollution cases and acoustic monitoring sensors for ISR of vessel interactions.

Following a reportable marine casualty, a timely response is essential to conducting a proper investigation to identify causal factors in addition to assessing and managing the safety of the scene and surrounding environment. As the lead maritime authority for such incidents, the USCG can take command of such a vessel within its jurisdiction. Marine casualties with larger impacts to the environment, ship, or mariners (categorized as a serious marine incident or to a higher-degree a major marine casualty) often involve questionable structural integrity of the hull. Underwater structural assessments, both at a casualty's scene or pier-side, are especially important for vessels carrying hazardous materials, such as oil, and can cause significant delays to maritime commerce using traditional dive teams that are time and manpower intensive.

To expedite the USCG's response, the use of UMS by marine investigators to autonomously survey the hull would mitigate personnel and environmental risk while providing decision makers with needed information. Figure 2.5 shows the Office of Naval Research's *HullBUG* [8]

which has been developed for autonomous hull cleaning on large ships but could be modified as a rapidly deployable hull survey UUV to enhance USCG marine safety capabilities. In addition, this UUV could be used during standard inspections, domestic (U.S. flag) and port state control (foreign flag), to inspect and record the structural integrity of the hull at a much more frequent rate than dry-docks with better oversight, while mandating no additional industry cost. Finally, this type of UUV could serve its designed function of hull cleaning on in-port USCG cutters when not needed for marine safety applications, aiming to reduce biofouling which increases ship performance by way of less fuel consumption due to less drag.

Figure 2.5: ONR's HULLBug promises to reduce vessel's maintenance cost by autonomously cleaning bio-fouling from the ship's hull at regular intervals in leiu of the existing need for expensive drydocks and harsh anti-fouling coatings. From [8].

A hull survey UUV would ideally be man-portable, easily launched or recovered from shore or a small rigid-hulled inflatable boat (RHIB). It would require strong real-time communication for necessary dynamic re-positioning and directed survey for efficiency and effectiveness especially in time-sensitive scenarios. To survey the deepest draft ships, a minimum of 80 feet of water depth tolerance would be necessary.

Capability Factors

Persistence: This factor is rated as low-moderate because of the moderate seakeeping characteristics required for hull navigation, including depth and localization. It is relatively low because it does not require long endurance compared to other mission packages.

Coverage Area: Low coverage area because it's mission is confined the the size of the ship's hull.

Timeliness: In response to a marine casualty, this would be moderate-high to quickly provide

information for decision makers that could impact the safety of the crew, cargo, and the environment. Timeliness is also a large motivation over traditional mechanisms for hull inspection such as manned divers.

Command and Control:Ideally, this UMS would require low command and control to search the ship's hull. Autonomous search and simplistic communication requirements inform this rating.

Perception and Prosecution: Perception would be moderate to identify hull anomalies and suspect areas for further inspection.

Autonomy: This factor is seen as moderate-high because of the necessity for autonomous search to most efficiently survey the hull in a timely manner. Due to curvature and localization challenges, this presents complexity in the UMS autonomy for this mission package.

Environmental Integration: This is a straightforward tasking UMS with no implications for ISR signature or observables, resulting in a low rating.

This subsection's capability factor rankings are shown in the overall capability factor ranking summary seen in table 2.3.

2.3 UMS Capabilities Analysis

The Capabilities Analysis section of this work provides a baseline relationship between near-term USCG capability gaps and mission needs with associated UMS capabilities required to meet those demands. Building on the CONOPS, this section will utilize a "solution-neutral" approach to the problem, meaning a specific UMS is not explicitly identified but rather its necessary capability factors and attributes are analyzed. Finally, USV/UUV characteristics and mission package relationships are recommended in the capabilities summary.

2.3.1 Capabilities Summary

By categorizing UMS mission package capabilities with a consistent taxonomy, several UMS capability commonalities and trends emerge. These trends provide the basis for notional alternatives for USCG UMS, but are not so explicit as to define final system requirements. The mission package commonality also provides insights as to the degree to which certain alternatives may be utilized across missions, providing a tradespace with regard to operational quantities vs. capability vs. affordability, quantities vs. logistics, etc. Configuration of the UMS with manned

assets also play a considerable role. Table 2.3 shows an overview of the relative ratings, using a Likert scale from 1 as low (red) to 5 as high (green) required, between mission package capability needs based on the CONOPS capability factors discussed earlier this chapter.

Mission Packages / ***Capability Factors***	Persistence	Coverage Area	Timeliness	Command and Control	Perception and Prosection	Autonomy	Environment Integration
Buoy Augmentation	5	1	1	2	1	1	5
Temporary Aids to Navigation	3	2	3	3	2	3	5
Diaster Relief	3	3	3	4	3	4	4
OTH MDA	4	5	3	4	4	2	4
Port Security	3	3	3	4	4	3	3
Remote Location	5	4	1	2	4	2	1
Security Escort	2	3	5	4	4	5	5
Living Marine Resources	5	5	1	2	4	2	1
Marine Environmental Protection	3	4	3	3	5	3	2
SAR	5	4	5	3	3	3	1
Marine Safety	2	1	4	1	3	4	1

Table 2.3: The mission package capabilities summary provides relative ratings amongst the sample set. Persistence is observed as the most influential capability factor.

Interestingly, even within statutory missions such as Aids to Navigation, there is a fair disparity between capabilities based on the representative mission packages of Buoy Augmentation and Temporary ATON; or Maritime Security with OTH MDA, Port Security, and Remote Location. These ratings support the observation that functional capabilities are not uniform within a mission, and it is more likely that elements of different missions are more closely aligned in terms of capabilities. This work uses radar charts to communicate the commonality between an individual mission package's capability factors such as persistence in comparison to other capability factors for itself and comparable mission packages.

A common trend from the representative mission packages is high persistence coupled with low timeliness. This is seen most clearly between buoy augmentation, remote location, and living marine resource. Further inspection shows one other key distinction between these for environmental integration, leaving remote location and living marine resource as possible candidates for a multi-mission UMS alternative. Another mission package that may require less persistence but similar factors is OTH maritime domain awareness, although it requires increased

timeliness for tactical operation. Figure 2.6 shows a radar chart of factors with fairly correlated rated.

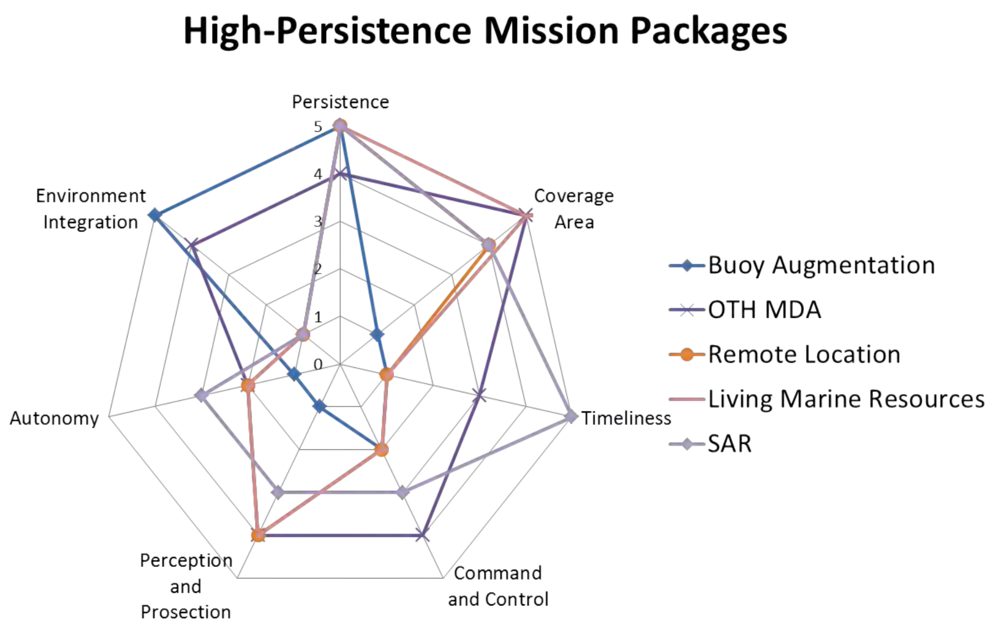

Figure 2.6: The high persistence mission packages represented in the radar char show fair correlation among other factors with the exception of SAR's high timeliness factor.

Figure 2.7 shows a strong correlation between moderately rated persistence mission packages. Marine environmental protection was not expected to accompany port security or disaster relief due to their distinct CONOPS. These mission packages also included the least specificity in regards to domain specific advantages, allowing both UUVs and USVs as candidate vehicles for their UMS.

Conversely, mission packages with low persistence present the least correlated sample. Although marine safety and security escort typically occur near coastal and harbor areas they have drastically difference functions. The security escort mission package, by nature, utilize a surface craft as to deter and engage hostiles which requires high degrees of both autonomy and environment integration (collision avoidance, networked navigation). Figure 2.8 shows a radar chart for low persistence type mission packages.

Mission packages with similar capability factor rankings require a more in-depth comparison to flush out the best candidates for the multi-mission UMS alternatives developed in Chapter 3.

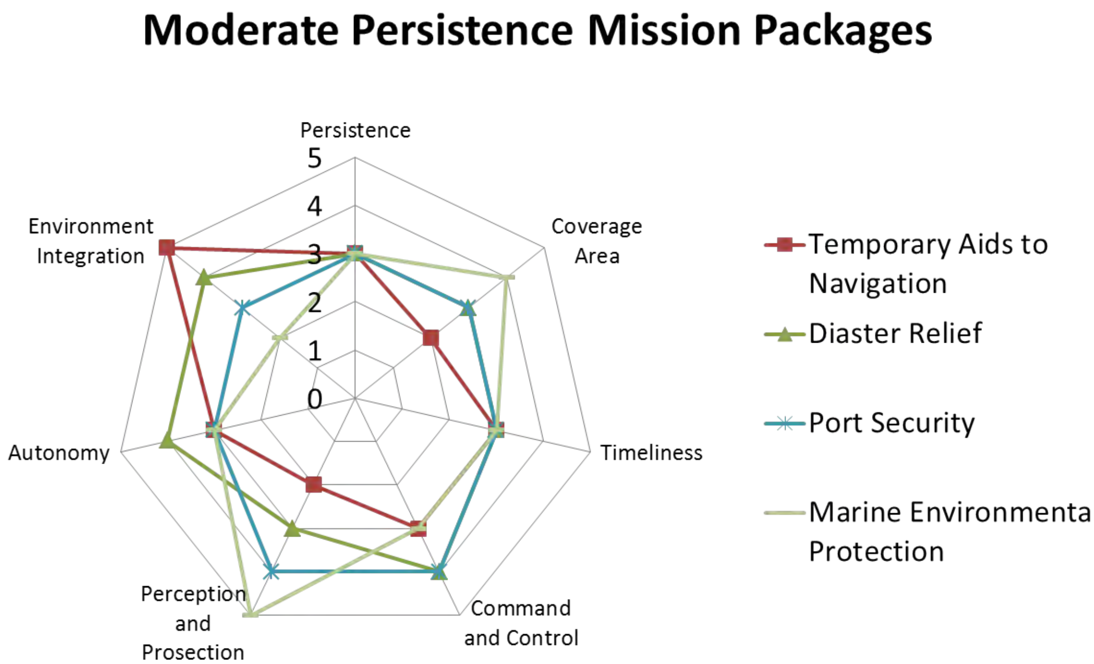

Figure 2.7: This moderate persistence radar chart shows a strong relationship between unlikely pairings of marine environmental protection and disaster relief. Further analysis is needed to draw more insights for a multi-mission UMS.

Temporary aids to navigation (ATON) and disaster relief show high correlation for most factors and can logically be coupled if assuming a surface craft, but become divergent for underwater UMS which is a poor fit for to any ATON. Similar observations can be made about high persistence packages with SAR as the outlier due to its high timeliness rating. For the MEP mission specifically, there are several other notional applications that would change the assigned factors beyond oil in ice. Additional analysis of multi-mission capability factors and other system elements is provided through Chatper 3's alternatives and system architecture.

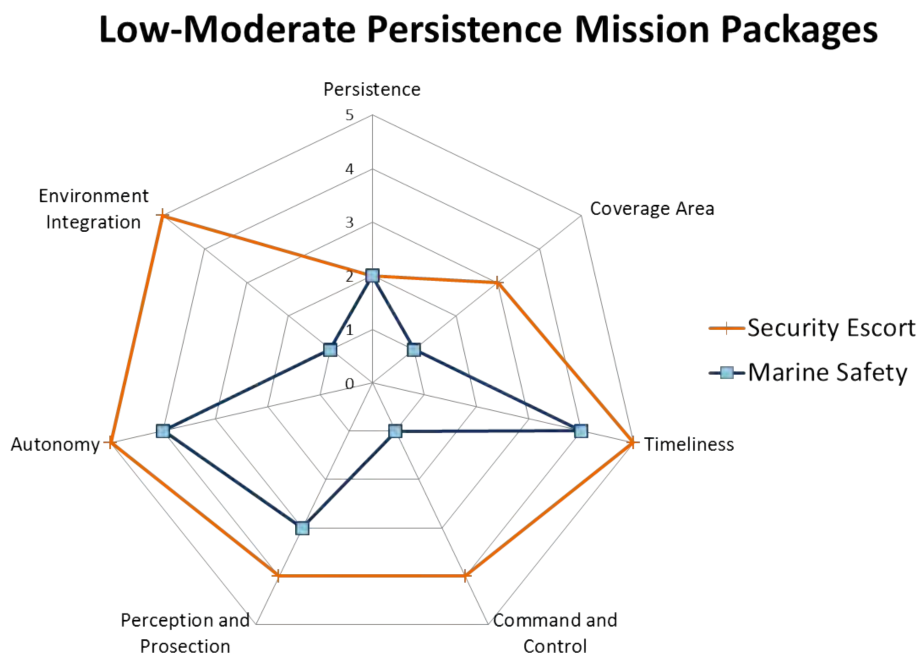

Figure 2.8: The low-moderate persistence mission packages are the least correlated sample of non-persistence factors.

CHAPTER 3: UMS Alternatives and System Architectures

This chapter details three USCG UMS alternatives built upon the understanding that a multi-mission UMS with similar capabilities and near-term system/technology readiness will more likely be acquired than a single-mission or application-specific UMS, offering limited reuse and flexibility. Size is another consideration implied but not prescriptive in each alternative. The intention with regard to size is choosing the best suited vehicle for a given set of missions, affordability and usability which is projected to result with more options in smaller platforms [44]. Alternatives are derived from commonalities in operational activities discussed in the CONOPS and their respective capability needs, with details on capability assumptions provided in Chapter 2. The representative CONOPS are utilized as the framework for operational architecture(s) for each alternative, which are abstracted into the system's functional and physical architectures to provide traceability, along with future design and feasibility considerations. To justify a proposed system-level design for a particular UMS alternative vehicle characteristics are discussed, while not choosing an existing commercial example of a UUV or USV. Noting that commercial examples do provide a good context for the state of current system and technology readiness, as well as near-term capabilities and cost estimates discussed in more detail in Chapter 4.

3.1 Derived UMS Alternatives

The three alternatives are broadly categorized by their probable operators, key capabilities, and domain as follows:

- (1) Cutter-Based Tactical UUV
- (2) Shore-Based Harbor/Coastal UMV
- (3) Operational Offshore USV

These distinctions are system design elements with trade spaces between and within each of them. For instance, a common relationship between operator and capability is exemplified by the forecast that as autonomy and communication capabilities increase in the future, it is likely that an alternative's operators will become less prescriptive through improved usability for various types of operators. Due to this uncertainty, this work assigns operators from the organizational level to which the UMS is deployed and controlled (i.e., Cutter-Based describes a UMS used by the National Security Cutter or Offshore Patrol Cutter). System-level capabilities are

vital in the categorization of a particular alternative. Some mission packages are not explicitly included in a given alternative; this is partially attributed to the uniqueness or current infeasable nature of certain desired capabilities. Domain distinctions are also critical for system design. Even though the UMS missions for undersea and surface vehicles may be similar from a needs analysis perspective, there are specific challenges with each domain that are considered within the alternatives [34]. For example, a challenge for unmanned surface navigation is adherence with COLREGS whereas communication capabilities present challenges in the undersea domain. Two of the alternatives involve the undersea domain, in part to combat the current limited USCG undersea oversight and response capabilities. Every alternative aims at providing the best capabilities through the unique advantages of UMS to the given USCG operator within the near-term.

3.1.1 Cutter-Based Tactical UUV

To enhance the effective range of USCG assets, especially offshore, the *Cutter-Based Tactical UUV* alternative is most correlated to the Maritime Security over-the-horizon MDA mission package. This diverse mission package includes drug interdiction, migrant interdiction, defense readiness, and other law enforcement. Additional USCG roles and mission packages also apply to this alternative including the marine environmental protection's mission package, described in Chapter 2. This alternative's key capabilities include high persistence, large coverage area, and high perception. Ideally suited to travel distances in excess of 80nm within the course of hours to days with sensors capable of perception qualities sufficient to effectively identify illegally operating vessels and underwater threats. A reduced ability for environmental integration capability is necessary due to the offshore undersea area of responsibility containing limited collision risks and navigation hazards. The choice of an UUV for this alternative is both practical from a navigation and power consumption perspective but also enhances the low-signature quality desired for ISR-type missions.

This alternative would also serve as a complement to cutter boats, small (26-35ft) high-speed boats with pursuit, interdiction and rescue capabilities, such as the Long Range Interceptor-II (LRI-II) and Over the Horizon-IV (OTH-IV) [45]. To reduce cost and logistical burdens, suitable cutter boat hardware could be utilized, such as launch and recovery from the ship's davit or stern launch and maintenance by the ship's crew. Similarly, the upper-bound size and weight of this UUV is prescribed by available shipboard shape and launching capacity, while smaller UUVs may offer acceptable capabilities. Minimal command and control (C2) requirements are anticipated because of the autonomous navigation and route-following abilities with periodic

surfacing for short periods to facilitate communications and re-tasking. As underwater communications improve the same vehicle could more feasibly handle a wider range of mission packages.

Commercial examples of a representative UUV include the *Slocum* glider and the *Bluefin Robotics's* various models [9], [46]. These examples provide the technological foundation for platform, navigation and control, and launch and recovery. Less mature technologies for this alternative include vessel detection and classification sensors configurations along with networking/interoperability between UMS and other external U.S. forces, such as the U.S. Navy.

This alternative, and other cutter-based UUV, has the potential to provide some secondary applications such as a deployable communications node or chemical, biological, radiological, and nuclear (CBRN) detection and monitoring device, specifically for an underway USCG cutter or USCG air asset.

Figure 3.1: The Slocum Glider manufactured by Teledyne Webb Research is a type of UUV driven by buoyancy. A wide variety of physical and optical sensors enable numerous applications from environmental monitoring to maritime security. Large coverage area capability is showcased by a single set of alkaline batteries providing 600km range. From [9].

While USVs could play a role for this alternative, sea-state limitations on seakeeping properties in combination with the need for higher persistence capabilities provide the basis to down-select. Energy demands are another primary factor to reject USVs for this alternative. Also, other cutter-based UMV are not included in this alternative but are feasible applications for future analysis. The USN Harbor Class USV and representative platform *Seafox* is a good example of a potentially ship-based USV that has comparable capabilities to the cutter boats. This class of USV highlights the potential capability of manning an unmanned vehicle with limited conversion time. Bluefin's *Proteus* exemplifies this "dual mode" concept as it has been

developed for UUVs to accomplish manned missions such as USN Special Forces delivery [47].

3.1.2 Shore-Based Harbor/Coastal UMV

This alternative provides enhanced MDA in harbor settings with potentially faster response than manned assets the undersea domain especially for ports, waterways, and coastal missions. It also has the most diverse set of mission packages and associated variability in specific capability needs. This diversity lends itself to a modular approach to UMS design focusing on two basic variations per domain: (1) UUV for marine safety and port security and (2) USV for Disaster Relief and Temporary ATON. This alternative combines the two domains because the UMS will share the same operators and capabilities.

USCG shore-based operational units in charge of ports and harbors, such as Sector Honolulu, would utilize this alternative in various configurations, in conjunction with or without manned assets. The UUV variant seeks high levels of perception and autonomy capabilities to effectively meet the challenges of hull integrity survey, underwater terrorist threats, and illegal underwater drug trafficking. The timeliness capability is moderate because the proposed launch and recovery are within a harbor type area with limited to moderate coverage area. For higher timeliness demands, teams of this alternative could more easily meet the demand with regard to current single UUV speed capabilities [30]. The USV variant uses the same operators with similar capabilities but provides more persistence, which is more feasible due to more choices in renewable energies for USV persistence. Modularity of sensors, interfaces and communication components also contribute to the complexity of this alternative, which will likely increase maintainability concerns but also improve its flexibility and reuse.

This alternative does not include Force Protection type USVs which do have direct application for the USCG mission package Security Escort, such as the USN *Seafox*. These classes of USV are being planned, developed, and designed for comparable applications which may prove useful for the USCG but do not currently present an area for unique USCG applications. A comprehensive USCG UMS Roadmap would evaluate the use of such USV and its interoperability between forces, but this is beyond the scope of this work because of the limited focus on USCG-specific UMS.

3.1.3 Operational Offshore USV

This alternative has a primary objective of enhancing MDA through strategic positioning and intelligent patrols to combat remote location and offshore threats. While offshore interests may

be viewed as less of a traditional priority for USCG missions [48], several missions would benefit from fairly simple sensors in addition to general MDA. This alternative is suited best for missions applications such as living marine resources and foreign fishing EEZ encroachment, which occur in remote areas with limited CG presence such as the Arctic and Northwest Hawaiian Islands.

Key capabilities necessary are high persistence and large coverage area with moderate perception capabilities, and low timeliness. The surface domain is chosen for the best possible communication accessibility and, more importantly, persistence qualities, while considering that offshore areas present less navigation risk. Operation of this alternative could be utilized from shore, cutter, or air assets with minimal preference because of the high autonomy and range. The surface domain also presents various sources of renewable energy, such as wind and wave power, for longer persistence.

Representative commercial examples of this type of USV are the Liquid Robotics' *Waveglider* and conceptual USV from Harbor Wing Technologies, shown in Figure 3.2. These showcase various sources, i.e., wave and wind, of sustainable energy enabling high persistence capabilities [10]. They also demonstrate the potential, with more advanced perception, to carry out this alternative's mission packages described in Chapter 2

This alternative's key capabilities are also comparable to the Buoy Augmentation mission package, although this mission package is not specifically included. The buoy mission package has several policy challenges concerning its ability to not only perceive information but also disseminate it that make its inclusion in this alternative weak. This type of special application would be a useful consideration for future studies.

3.1.4 Alternative Summary

Table 3.1 shows a summary of the alternatives with corresponding capabilities, USCG Role and Mission, derived mission packages (See CONOPS), and representative commercial vehicles. The vehicle represents an example of the current technology and physical components.

3.2 System Architectures

System architecting is a unique aspect of systems engineering (SE) and has been said to be both an art and a science. According to Maier and Rechtin, "the foundations of systems architecting are a systems approach, a purpose orientation, [and] a modeling methodology." [49] In keeping

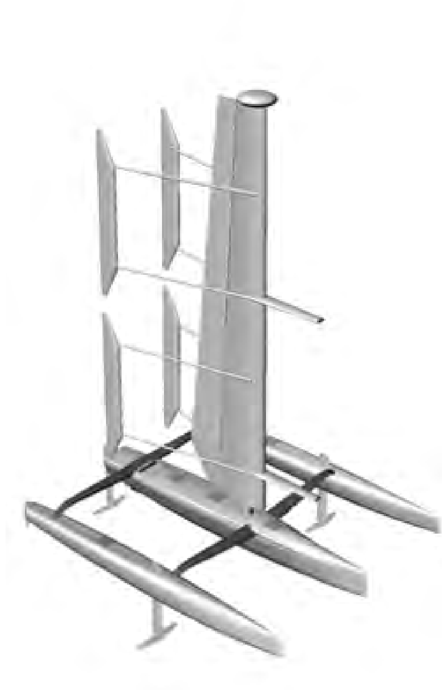

Figure 3.2: The Harbor Wing Technologies X-3 is utilizes wind energy to reach speed in excess of 25kt and ranges of 500nm. It's design is well suited for offshore applications with high persistence requirements, stating a time at sea of three plus months. From [10].

Multi-Mission Alternative	*Key Capabilities*	*Statutory Missions*	*Derived Mission Packages*	*Representative Commercial Example*
Cutter-Based Tactical UUV	Med-High Persistence	Drug Interdiction	OTH MDA	Slocum Glider
	High Perception	Migrant Interdiction		
		Defense Readiness		
		Other Law Enforcement		
		Marine Environmental Protection	Marine Environmental Protection	
Shore-Based Coastal UMV	High Perception	Aids to Navigation	Temporary ATON	ASC Sea Rover Concept
	Med Timeliness	Marine Safety	Marine Safety	ONR HULLBug
	Med-High Autonomy	PWCS	Disaster Relief	
		PWCS	Port Security	Bluefin HAUV
Operational Offshore USV	High Persistence	Other Law Enforcement	Remote Location	Wave glider, Harbor Wing Technologies
	Large Coverage Area	Same as Above	OTH MDA	
	Low Timeliness	Living Marine Resources	Living Marine Resources	

Table 3.1: This table maps the each alternative with key capabilities, mission and mission packages discussed in Chapter 2 to emphasize the multi-mission qualities. To provide a notional idea of system design and technologies, commercial examples are listed for each alternative.

with the systems approach, "architecture" often refers to the holistic system and how it interacts internally and externally, focusing more on an system element's relationships and combined performance rather than the individual characteristics. The primary focus is to ensure that the

overall system satisfies the capability needs, and provides coherent documentation while not necessarily optimizing any one element. Simply put, the systems overall ability to carry out its mission based on set requirements is more beneficial than it optimizing a specific attribute, such as speed. The interaction between the operational user, functions, and components for each alternative are examined to iterate the analysis and incorporate meaningful feedback for individual and combined perspectives. To accomplish this, a model-based systems engineering (MBSE) methodology is used in the software platform Vitech Core 8 (University Edition) [11]. This work utilizes MBSE as a tool, where its primary focus is to provide a foundation functional mapping for feasibility considerations, omitting a large portion of the system design characteristics. The standard Vitech Core 8 schema is utilized to provide standard definitions of relationships between elements, i.e., a “Component” performs a “Function.” Figure 3.3 visually depicts these relationships, some of which are discussed in detail throughout this chapter.

3.2.1 Operational Architecture

The operational architecture of the system affords the system designers a means of capturing a wide range of feasible system operational uses and understanding of the interdependent relationships within the system. Using the operational architecture, the system designers have a way to ensure that the system design is capable of accomplishing its intended purpose and requirements. The mapping between mission, operational activities, performers and functional architecture validates the overall system. Many of these elements are captured in the CONOPs section of this work, but are only mentioned here as a consideration. The latter functional and physical architectures provide a more logical flow and mapping for the system overall.

3.2.2 Functional Architecture

To lay the foundation for a functional architecture, a high-level master functional decomposition is first developed for USCG UMS. This master decomposition captures the vast majority of UMS functions in a top-down approach for all three derived alternatives, noting that their physical architectures are to be developed separately in more detail. From the high-level, several key functions and their associated challenges emerge as areas across alternatives that warrant more investigation on system feasibility which is discussed in Chapter 4. Also, some functions encompass the system as opposed to the UMS which includes human operator, maintainability, logistics, and policy functions.

Each alternative provides a more detail-oriented functional “composition” or bottom-up approach resulting in the overall system being developed conceptually “middle-out”. This type of

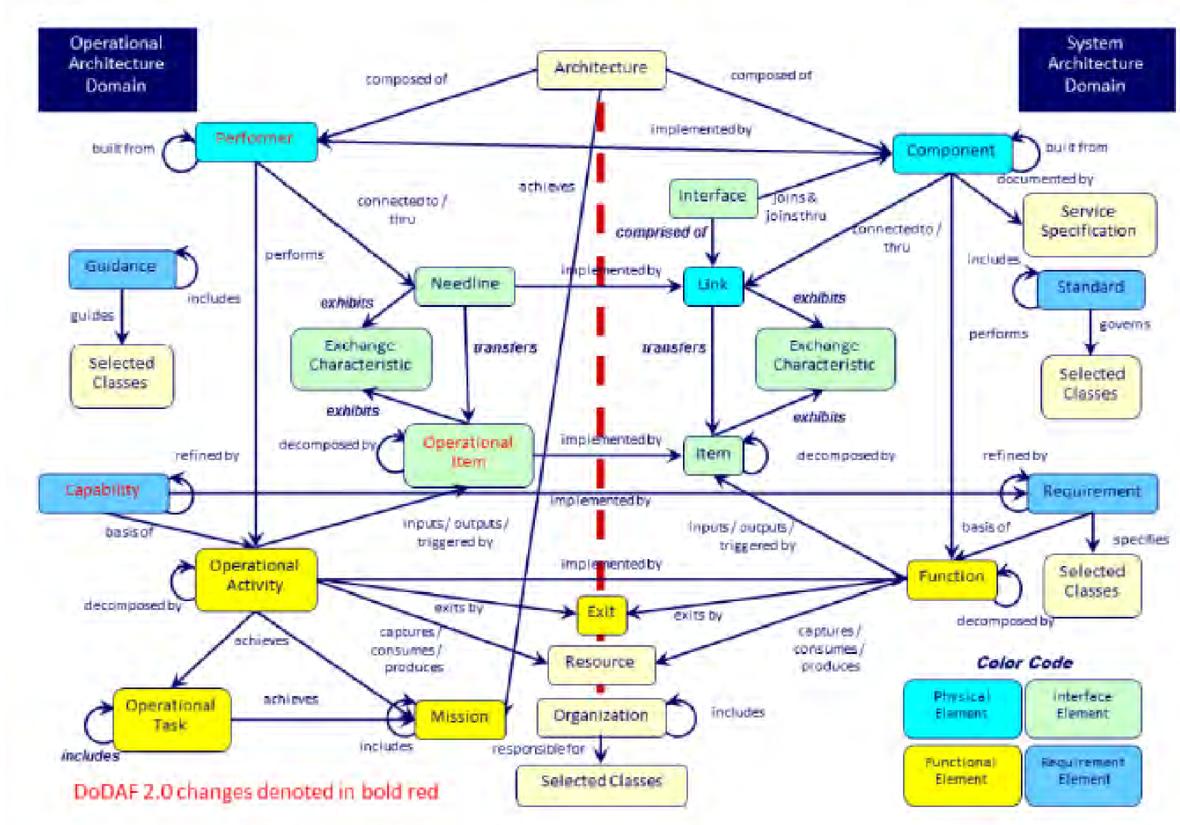

Figure 3.3: Vitech Core's Schema shows the syntax and semantics for this particular software based MBSE. By using common definitions to map system elements, information is easily shared from various views within a architectural framework. From [11].

composition is favored for more unprecedented types of systems, arguably befitting any USCG UMS [50]. In addition to the methodology as to how this hierarchy is developed, consideration is taken with regard to the function's inputs, controls, outputs and interfaces. Many functional terms are intentionally vague to more easily apply across multiple UMS platforms. For example, F.1.2.6 Comply with Navigation Rules, does not denote which specific navigational rules in the event that UMS may have its own unique rules or policies. Finally, the functional architecture stays within problem space and speaks to "what" the UMS must do, without specially stating the "how." Figure 3.4 shows the UMS Master Functional Decomposition as a starting point for system design.

For clarification, definitions for the first level functions are provided here:

F.1.1 Command UMV This function takes the inputs of the user to control mission tasking, degree of autonomy, re-positioning, and launch and recovery (initiation and termination of mission). Heavily routed in command and control capabilities, it also relates to the usability controls on the system.

F.1.2 Navigate Area of Responsibility This function captures the baseline seamanship, to whichever degree of autonomy, and has a firm control by navigation rules.

F.1.3 Communicate Information This function is straightforward communication between the operator and vehicle, and also to and from other maritime entities, either friend, foe or neutral party.

F.1.4 Process Information The ability to process, compute, categorize and manage information is captured in this function. Data storage from UMS may also be critical for effective future enforcement action against threats.

F.1.5 Manage System This function broadly summarizes the non-vehicle functions of the UMS, including training and qualification of operators, maintenance, policy, and logistics.

F.1.6 Perceive Area of Responsibility This function is at the heart of UMS mission needs, from high to low persistence, the need to sense the UMS surroundings with a sufficient degree of fidelity is paramount. This function is the most varied with physical components for alternatives.

F.1.7 Monitor Status This function is seen as the systems ability to measure its status in terms of energy, signal strength, etc., as well as mission status in terms of deviation from way points,

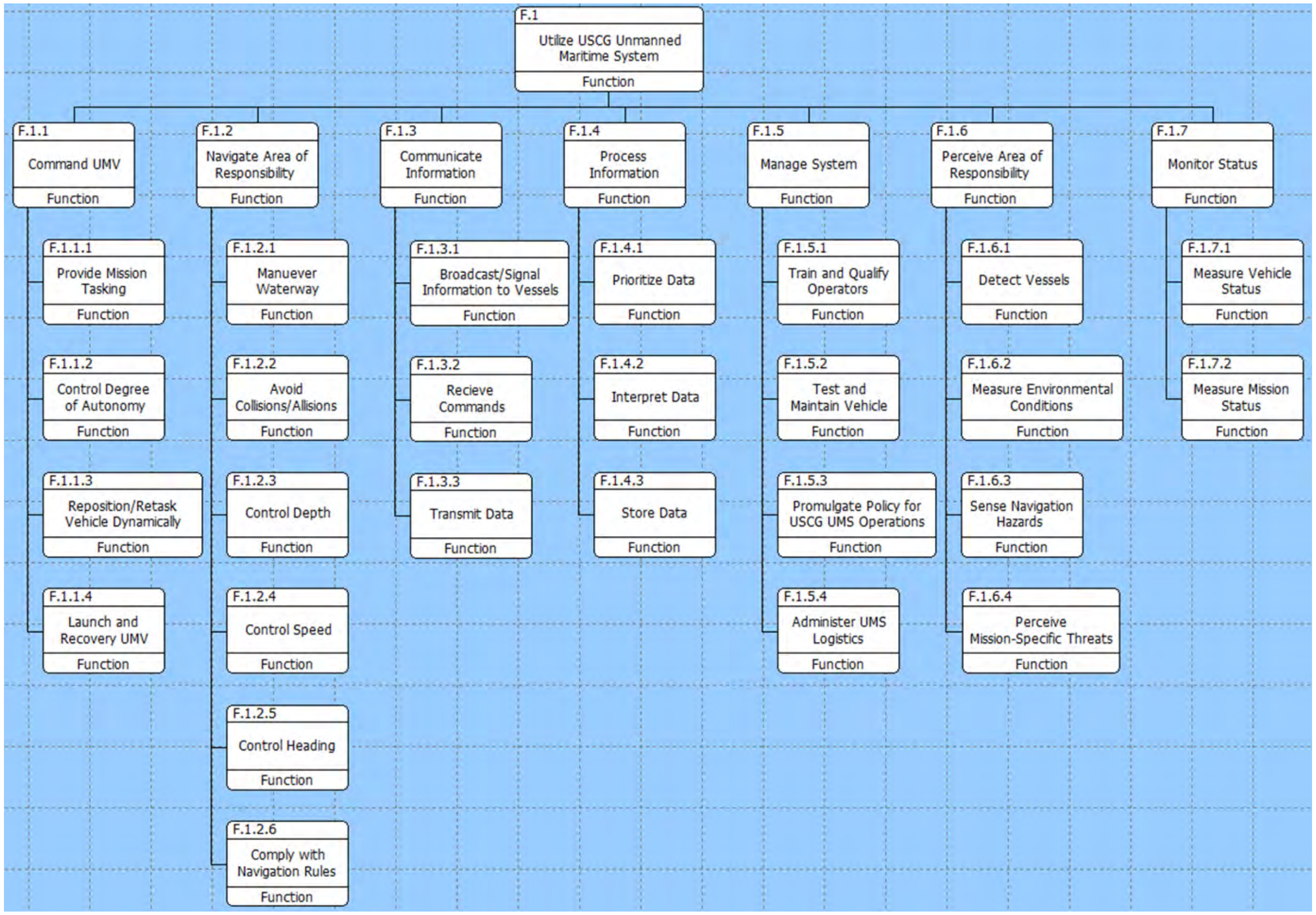

Figure 3.4: The master functional decomposition applies broadly to all three USCG UMS alternatives. The specific attributes of each function and their interrelationships is unique for a given alternative UMS.

communication equipment performance, etc.

3.2.3 Physical Architectures

The physical architecture provides the breakdown of component systems in conjunction with functional architecture. This includes more than just the physical vehicle as well, including software, personnel, policy and other tangible system components. It was developed generically in a top-down approach as a context to partition the system into greater detail as opposed to a more specific instantiated physical design due to inherent complexity and novelties of instantiated design even in more established systems [50]. Fortunately, even generic resource allocation provides meaningful insights for each alternative's analysis. While good SE practice, a one-to-one mapping from function to component is forgone in preference for a component(s) per alternative functional allocation.

Figure 3.5 shows the UMS master physical architecture which was developed to provide context, mapping, and eliminate any obvious mismatches with the master functional decomposition. Similar to functional architecture, physical components do have some aspects of solutions in mind but do present a large tradespace of potential options. Another important aspect of physical architecture is the interfaces and relationships between components, often informing the selection of other components. Such as the size of C.1.7 Vehicle Hull and C.1.8 Launch and Recovery component, where fairly simple physical choices from less than or over 200 lbs (and hull shape) will directly influence if the vehicle can be launched and recovered via a man-portable method or requiring a pier-side berth.

Morphological analysis or boxes was introduced as early as World War II and provides a framework for several possible solutions to a common problem [50]. This approach relates naturally to strategic thinking about physical components of a future UMS and will be utilized to provide component options within the alternatives. There are an endless variety of combinations for these alternatives to optimize one component or another, so this section provide a survey of components and their generic advantages and disadvantages based on attributes. Without firm system requirements captured from communication with key stakeholders, down-selecting any further would provide little utility.

Many of the physical components for mission specific functions such as F.1.6 Perceive Area of Responsibility will depend highly on mission package even within same alternative. This motivates a modular design, seeking to minimize the number and complexity of interfaces if

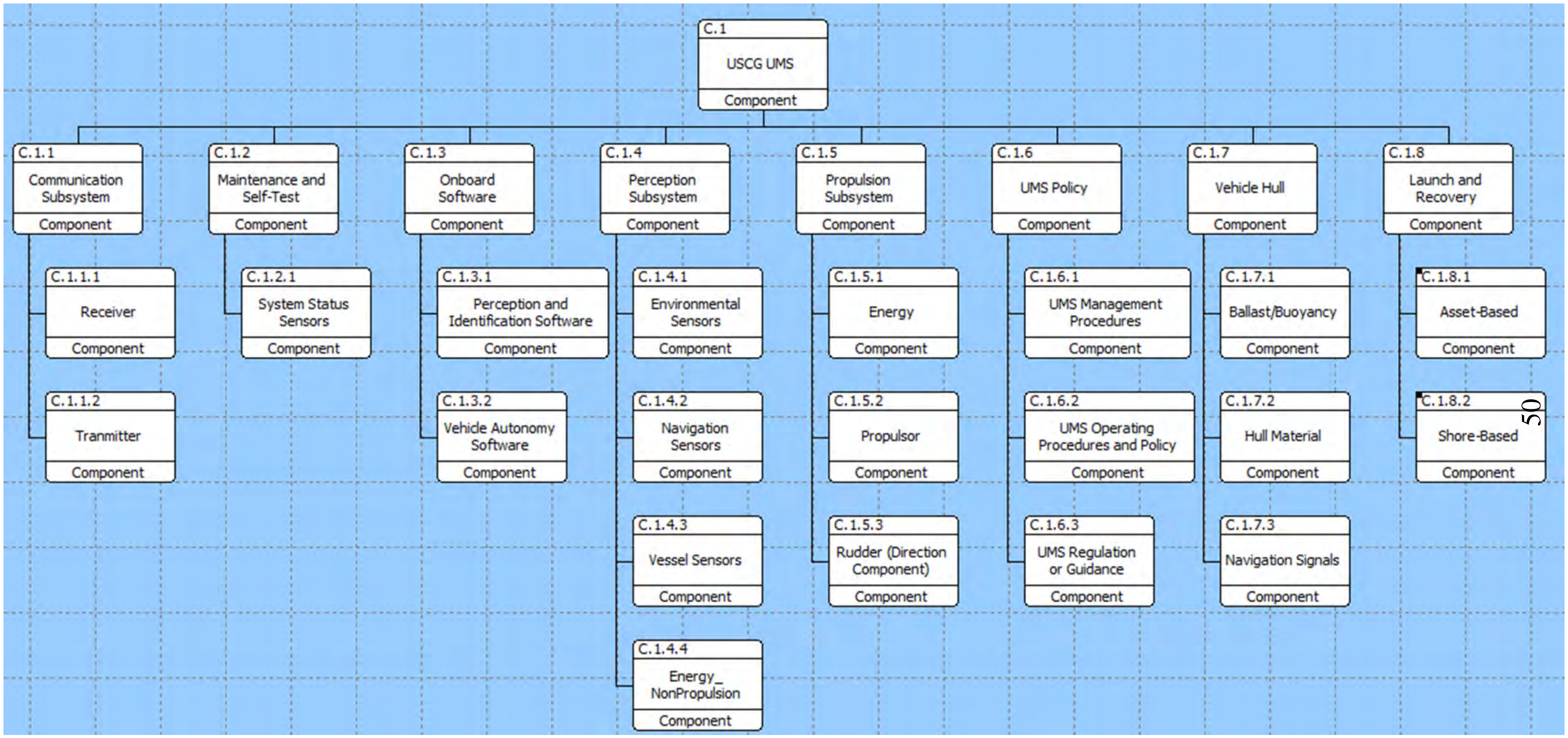

Figure 3.5: The UMS master physical decomposition provides a hierarchical breakdown of the vehicles physical components. Interfaces and functional mapping are integral system evaluation tools.

practical. For interoperability concerns, this desire is also echoed for software options that facilitate open architecture [15].

3.2.4 Systems Architecture Summary

This section has illustrated the importance of Systems Architecture in identifying relationships and informing eventual system design. Starting from a master UMS framework for both functional and physical architecture, it highlights system components with several options and others with limited technological readiness, discussed in more detail in Chapter 4. While the USCG may not be in the business of manufacturing or designing its own UMS, these high level considerations will help inform industry what specific USCG needs are required in their UMS from the operational, functional, and physical architecture perspectives.

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CHAPTER 4: Feasibility Analysis and Timeline

In this chapter, the near- and mid-term feasibility, approximately 2013 through 2023, of USCG UMS are analyzed by a survey of key system enablers (KSE) with their desired qualities. To further reinforce and map the effective mission needs with USCG UMS, applicable national maritime threat trends are projected over the same time period. Affordability, from both technical and organizational cost drivers, and risk are also critical aspects of any unmanned system, which leads to a discussion on their impact for each KSE in a time-phased methodology [51]. The three USCG UMS alternatives developed in Chapter 3 lay the foundation to compare KSE over a notional timeline. KSEs are categorized by technology, capability, policy, supportability and manpower. Finally, recommendations and mitigation strategies are proposed to increase the likelihood of earliest acquisition and implementation.

4.1 Unmanned Roadmaps and Challenges

The diversity of UMS in development and operational for military and civilian applications offers a plethora of information in regards to feasibility. Strategic documents for a given stakeholder such as the DOD's *Integrated Unmanned Systems Roadmap 2011-2036* and *A Roadmap for U.S. Robotics - From Internet to Robotics 2013* provide a vision for a given application or mission and its associated challenges. These documents enables many commercial entities to develop and design unmanned technologies to meet that vision. While the USCG UMS vision may be different based on the Coast Guard's unique mission needs and fiscal constraints among other factors, these documents provide much of the foundation for UMS overall, offering the USCG insight in developing its own projections and goals. In addition, regardless of USCG UMS acquisition, these roadmaps are also important for the USCG from a maritime law enforcement and regulatory perspective as more non-USCG UMS become operational.

A Roadmap for U.S. Robotics provides a five-, ten-, fifteen- year timeline of "Envisioned JCA Unmanned System Goals" for UMS in a chapter on defense robotics shown in Table 4.1. The Battlespace Awareness, Force Application, Protection, and Logistics joint capability areas (JCAs) have significant parallels to many USCG UMS missions, specifically in regards to COLREGS considerations, logistics, and collaborative networks.

The *Unmanned Systems Integrated Roadmap FY2011-2036* provides additional information for

	5 Year	10 Year	15 Year
Unmanned Maritime Systems			
Battlespace Awareness	Automated following COLREGs Remote sensor deployment Metal and plastic mine detection by UUVs.	Persistent automated surface and subsurface monitoring (user on the loop) Human detection by UUVs. UW Facility and infrastructure anomaly detection. Collaborative operations to operate as part of a wide area of detection.	Persistent automated surface and subsurface monitoring (user off the loop) with worldwide reach in all weather. Collaborative UUV operations to maintain detect and report on threat systems movement. Relocatable detection zones. Detection avoidance.
Force Application		Remote maritime threat interdiction response. Counter submarine capability.	Automated maritime threat interdictior response. SEAL team delivery.
Protection	Automated following COLREGs	Automated interdiction of manned and unmanned threats. Armed USVs and UUVs contributing to flank security.	Fully automated ship and shore installation security from maritime threats. Collaborative engagement of USVs and UUVs against a standoff threat.
Logistics UMV	• Automated refueling • Automated health monitoring • Automated hull cleaning • Continuous ship and shore installation inspection	• Automated UMV prognostics • Automated resurfacing and painting • Automated preventive ship and shore installation maintenance • Condition based UMV maintenance	Fully automated ship and shore basec operations (no operator hands on interaction).

Table 4.1: These goals provide defense and homeland security specific UMS capabilities within the next 15 years. Many goals have direct correlation to USCG UMS and help inform the USCG UMS timeline. From [11].

near-term technologies across all defense related unmanned platforms, including air, ground and maritime domains [4]. Table 4.2 and 4.3 shows the timelines for each system challenge including technologies that enable capabilities, in addition to their long-term vision (captured in the arrows) per challenge.

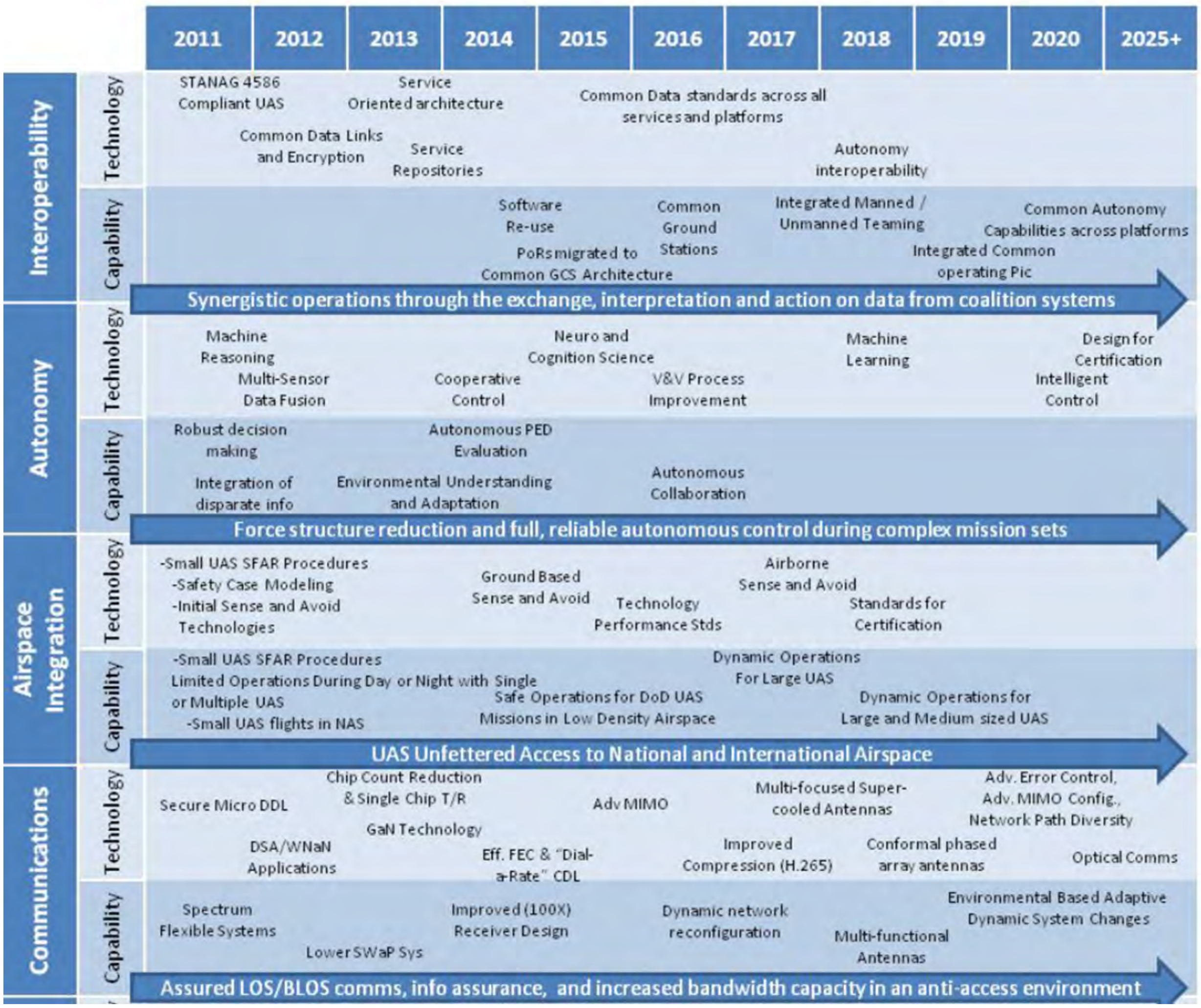

Table 4.2: This summary captures the most challenging aspects of unmanned systems from the DoDs perspective. Although some are domain specific such as airspace integration, correlations to the USCG exist such as maritime integration. From [4].

In a 2010 presentation titled *Meeting the Challenges of Unmanned and Autonomous System Test and Evaluation* by subject matter expert Thomas Tenorio [12], he provides a timeline focused around autonomy of unmanned systems for all domains. Figure 4.1 highlights some commonalities in timeline for autonomous behavior of unmanned system(s) and a given time period. This notion supports the assumption that although UMS are not the largest funded unmanned

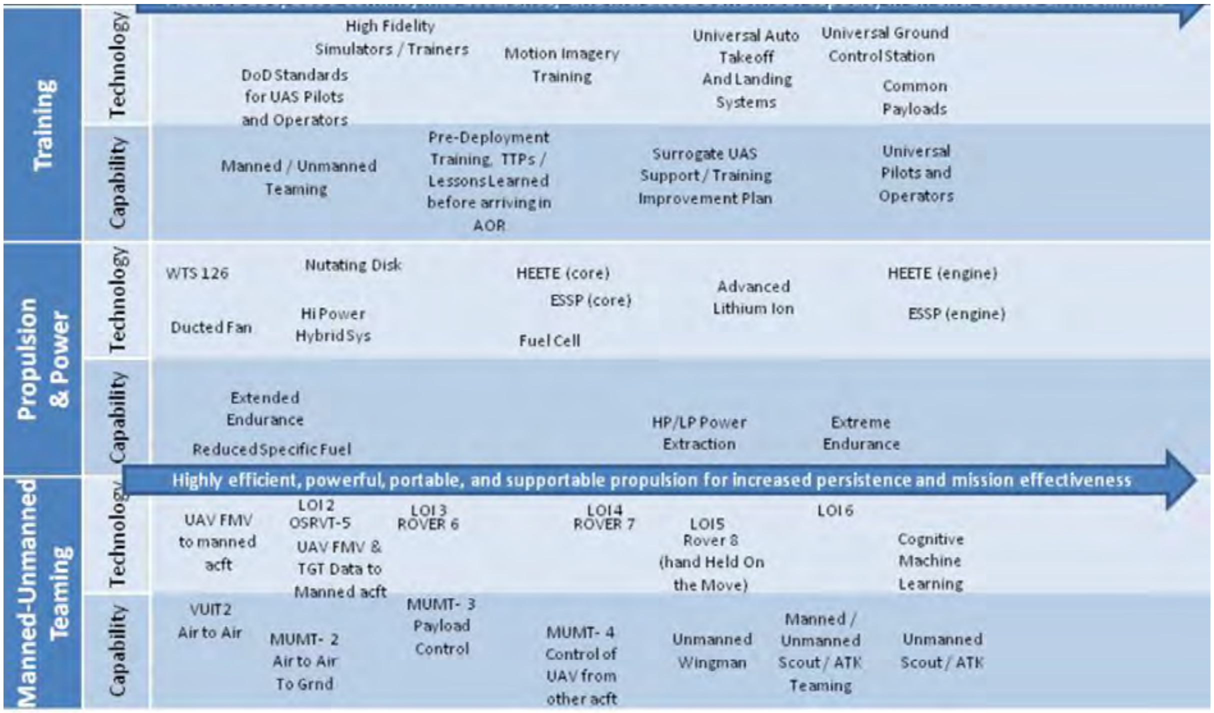

Table 4.3: This summary captures the most challenging aspects of unmanned systems from the DoDs perspective. Although some are domain specific such as airspace integration, correlations to the USCG exist such as maritime integration. From [4].

domain, advances in autonomy for other domains with more research funding such as air will likely offer additional autonomy capabilities.

These strategic planning documents provide sound background information for UMS and, specifically, interoperability considerations and requirements. However, the limited USCG stakeholder analysis within them presents a potential for uncertainty of assumptions that may adversely impact a USCG UMS utilizing a majority of system designs from external stakeholders. To mitigate this risk, more USCG interaction with these wider ranging plans as well as individual USCG studies would reduce the uncertainty to better clarify key USCG assumptions and perspectives.

4.2 Maritime Threat Trends

Global maritime trade and commerce has seen tremendous growth in recent years which has directly influenced the maritime domain's national security and economic importance [26]. This growth is naturally accompanied by an increase in the type, variety, and scope of tradition and non-traditional threats, many of which are discussed in this work as applicable missions for

Attributes	NEAR TERM (2010-2015) Tele-operated Systems			MID TERM (2015-2020) Multiple System Autonomy			FAR TERM (>2020) Collaborative Autonomy		
	Ground	Maritime	Air/Space	Ground	Maritime	Air/Space	Ground	Maritime	Air/Space
Exemplar Case Study	 Advanced EOD Robot System	 Surface Mine Countermeasure (SMCM)	 Broad Area Maritime ISR	 Autonomous Convoy	 Minefield Neutralize	 Unmanned Refueling	 Armed Robotic Wingman	 Anti-Sub Warfare	 UAV Combat Squadron
Sensor Capacity (Robot)	GPS, EO, planar laser	Sonar, beacons	GPS, INS, Collision Radar	EO/IR, Collision Radar, 3D laser	EO/IR, Sweep Radar, Sonar	Sweep Radar, EO/IR	EO/IR, Tracking Radar, 3D laser	Sweep Radar, Sonar	Sweep Radar, EO/IR
Perceptual Capacity (Robot)	Local map building and navigation, object avoidance	Open seas path following, Object detection and avoidance	Open air routing, Autonomous takeoff, landing	Vehicle sense and avoid, road navigation in urban environments	Rough sea position tracking. Wide area coverage	High precision maneuvering, Sense and avoid	High precision maneuvering, Complex behavior	Underwater localization, Complex behavior	High speed maneuvering in 3 space, track and destroy
Knowledge Orientation	Reactive World Model	Reactive World Model	Reactive World Model	Deliberative World Model	Deliberative World Model	Deliberative World Model	Adaptive Highly Representative World Model	Adaptive Highly Representative World Model	Adaptive Highly Representative World Model
Decision Capacity	Reactive	Algorithmic	Algorithmic	Complex Reactive	Complex Algorithmic	Complex Reactive	Complex Adaptive	Complex Adaptive	Complex Adaptive
Autonomy level (ALFUS)	1-2	3-4	3-4	4-6	4-6	4-6	6-10	6-10	6-10
Collaborative Capability	Individual / Multi system composite	Individual / Multi system composite	Individual / Multi system composite	Multi system coordination	Multi system coordination	Multi system coordination	Teamed Collaboration	Teamed Collaboration	Teamed Collaboration
Supervision level	Operator controlled Constant contact	Operator controlled Constant contact	Operator monitored Constant contact	Operator monitored Intermittent contact	Operator supervised Intermittent contact	Operator supervised Constant contact	Operator tasked Lengthy unsupervised	Operator tasked Lengthy unsupervised	Operator tasked Lengthy unsupervised
Mission Mapping to UMS JCAs	Battlespace Awareness, Protection Partnerships	Battlespace Awareness, Protection Partnerships	Battlespace awareness, Net Centric	Force Protection, Logistics	Force Protection	Force Protection, Logistics	Force Application, Force Support	Force Application, Force Support	Force Application, Force Support
POR / NPOR	POR	POR	POR	POR	NPOR	NPOR	NPOR	NPOR	NPOR
Mission Challenges	Task level, Single system, Sense and Avoid			Mission level, Multi system composition, Sense and interact			Battle level, Multi system interaction, Sense and Destroy		
T&E Challenges	Task performance, Personnel proximity, Environment representation, safety (inc. automation), endurance days			Mission performance, Multi vehicle proximity, Complex terrain representation, high speed operation, safety (inc. autonomy), endurance weeks			Team performance, Multi actor proximity, adversary representation, multi vehicle interaction, weapons release, safety(inc. collaboration), endurance years		
S&T Challenges	Sensory perception metrics, ground truth fidelity, measures of performance, Mission performance assessment			Behavior / decision complexity, assessment, Collaborative control,			Collaborative , Behavior adaptability assessment Lethality and Survivability assessment		

Figure 4.1: This timeline provides a holistic overview of unmanned systems across domains for defense applications. The anticipation of of autonomous capabilities synchronized improvement across domain supports the assumption that unmanned system capabilities benefit from extra-domain research. From [12].

USCG UMS. The *2013 Robotics Roadmap* supports the utility of UMS to combat threats by stating, “All maritime missions will benefit from reduced timelines and improved accuracy of information from which the combat commander can make engagement decisions” [15]. To build upon the maritime threats discussed in Chapter 1, there are three maritime trends specifically aligned with the capabilities UMS alternatives provide: underwater port security and anti-terrorism, desire for offshore MDA, and natural resources in the Arctic.

National reliance on the maritime domain, including ports, especially in light of terrorism and other loosely affiliated perpetrators of illegal activity has blurred many traditional lines at the operational level between USCG (homeland security), Federal Bureau of Investigation (FBI), and Defense [48]. In the future, these jurisdictional relationships will reinforce the need for interoperablity capabilities on UMS to best address multi-agency threats such as mine and underwater improvised explosive devices (UWIED) within U.S. ports. The ever-present possibility of a CBNR incident, either intentional or accidental, are apparent when considering the Fukushima Daiichi nuclear disaster and its follow-on radiation hazards [52]. In addition, recent increases in frequency of natural disasters such as Hurricane Katrina require first-responder assistance from USCG assets [1]. As these events occur more often and present more risk to human life, coupled with limited resources and damaged infrastructure, the utilization of UMS can aid in the safety and persistence of recovery efforts [39].

As maritime commerce grows, the needs for offshore maritime domain awareness are increasing because of the number and variety of threats, discussed in Chapter 1. In the near-term, augmenting existing USCG systems such as Nationwide Automatic Identification System (NAIS) with offshore UMS could enhance the effective range well beyond its current capability of approximately 50 nautical miles [53].

The availability of natural resources such as fishing, oil and gas, and minerals is projected to become more scarce in the near future. As new techniques and areas within the U.S. EEZ become available to harvest these resources, the potential for illegal activity increases. The Arctic’s reducing ice-sheet, due to warming at twice the global rate [24], presents challenges for both capability and resource allocation from the current USCG that may be aided by USCG UMS. Some models have anticipated the Arctic will exhibit ice-free conditions by 2030 [54], presenting a vast new expansive coverage area for the USCG within the next 20 years.

As UMS platforms become more and more common in the marketplace and costs fall, potentially unforeseen threats may emerge from the accessibility of UMS by more nefarious maritime

players. This presents a near-term gap between response and threat capabilities [55]. To mitigate this risk, counter-UMS strategies and tactics will be important from manned and unmanned USCG assets.

4.3 Key System Enablers

The key system enablers (KSE) for the UMS alternatives are technology, capability, policy, supportability and manpower. The KSEs capture the major factors for UMS as a system to become operationally feasible for the USCG. Risk rounds out the discussion with respect to the individual KSE in each subsection.

4.3.1 Technology

The pace of technology has been a enabler for unmanned systems in recent years and continues to push the limits of how they are being utilized. One of the major drivers for technological improvements has been the ability to design and develop UMS for civilian and defense applications in an modular open architecture framework [15].

To identify the stage in development for a given technology, technology readiness levels (TRLs) are assigned to a particular aspect (i.e., hardware or software) of a system. TRLs are defined in Figure 4.2.

Fortunately, due to advances through research and development of UMS over the past decade, many technologies incorporated in the USCG UMS alternatives are at TRL 9. TRLs are generally agreed upon throughout industry, but still include some subjectivity, meaning their value is typically seen as providing a context for risk and feasibility for a decision maker. Notionally, the lower the current TRL, the more time and money are necessary to reach a fully operational level (TRL 9). Although alluded to previously, due to an overlap in unmanned technology uses, USCG UMS advances are likely to be developed by stakeholders external to the USCG.

Technology Readiness Level is useful when decomposing each individual aspect of a system but provides less utility when evaluating a complete system, which requires integration readiness considerations as well [14]. To encourage a system prospective for evaluating readiness, Figure 4.3 shows a graphic of a newer approach incorporating Integration Readiness Levels (IRLs) as part of System Readiness Level (SRL). IRLs are defined as the status of connections between the technologies. SRL is the overall system maturity appraisal which utilizes subject matter expert and technology developer input to incorporate TRL and IRL [14]. This is espe-

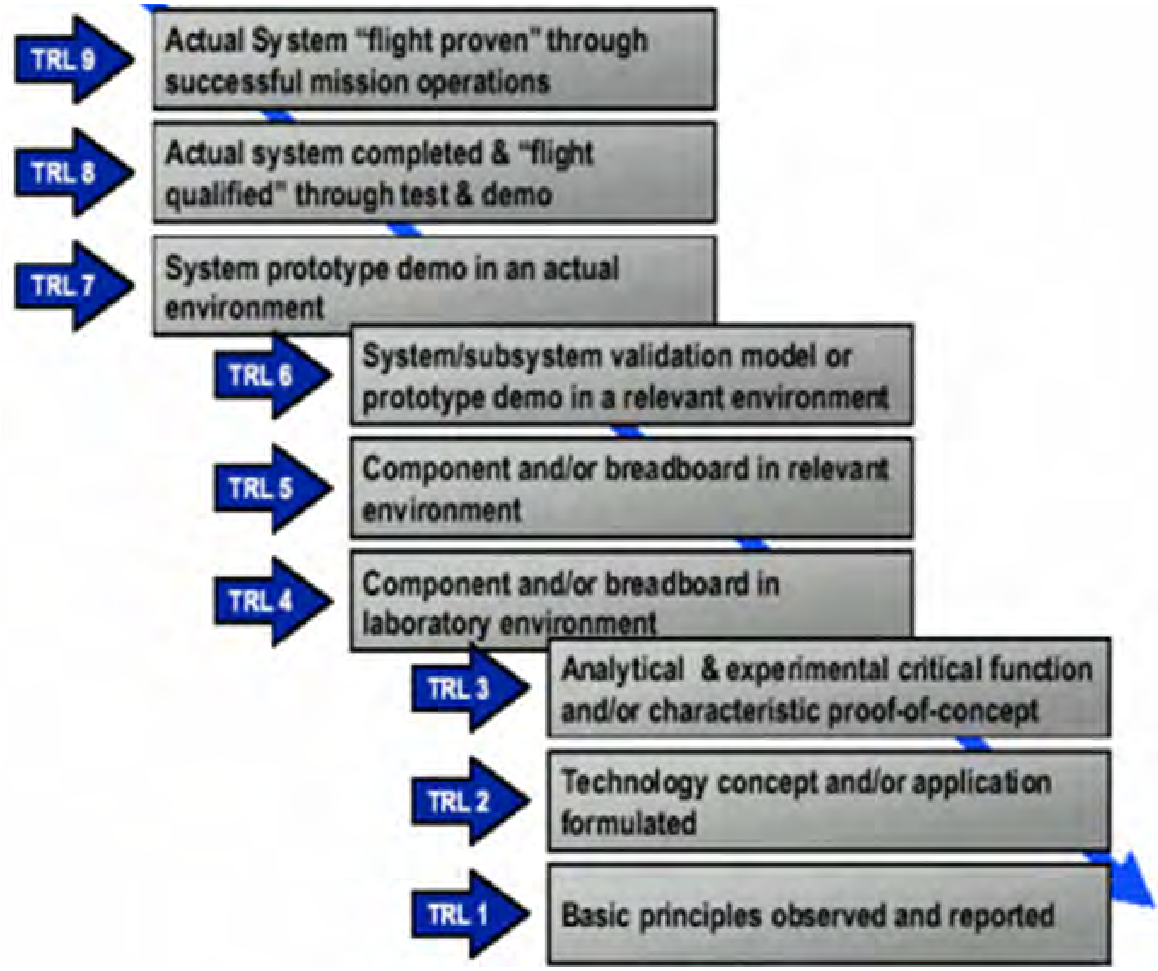

Figure 4.2: TRL definitions help decompose various component's maturity or developmental stage for a given system. From [13].

cially important in the maritime environment because of UMS's heavy reliance on interactions and integration as a basic tenet of its functionality.

Platforms: All three alternatives represent platforms that are currently at TRL 7 through 9, meaning they range from prototypes in the actual environment to actual systems performing successful mission operations. For example, the Cutter-Based Tactical UUV's commercial example, the *Slocum Glider* UUV, has thousands of hours of service and hundreds of operational systems making it a TRL 9 platform. Also at TRL 9, is the Operational Offshore USV's commercial example, the Liquid Robotics *Waveglider* is also fully operational and has logged trans-pacific voyages [56]. The Shore-Based Coast/Harbor UMS platform is more service-specific but variations of port security UMS have been field tested and are currently in development [39].

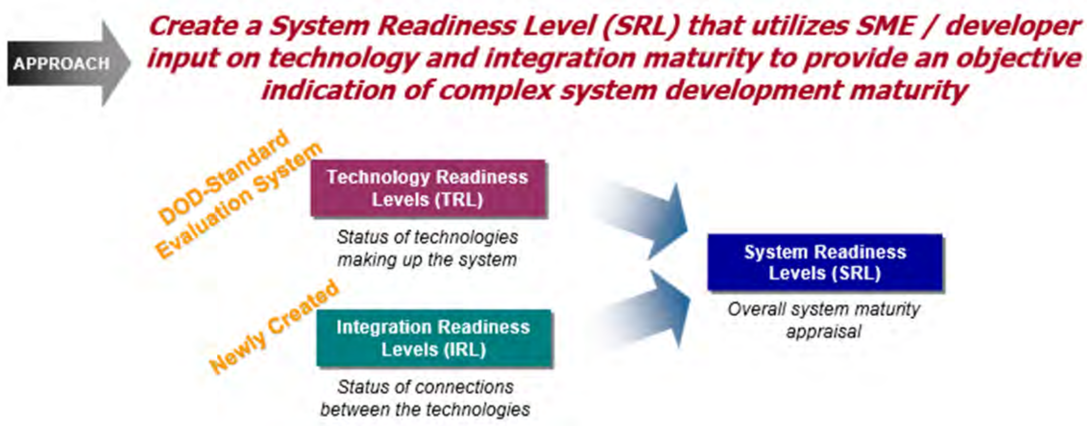

Figure 4.3: Combining TRL with IRL to formulate a SRL provides a more holistic approach to estimating maturity of a system for strategic planning and acquisition decision makers. From [14]

Navigation and Control: Technology for fundamental navigation and control has been fielded and operational, barring the complexities of increased autonomy, threat avoidance, and group behavior [13]. While enhanced capabilities for autonomy and group behavior are sought after for USCG UMS, they not necessary given the CONOPS described in Chapter 2. Cutter-Based Tactical UUV and Off-Shore Strategic USV navigation and control is at TRL 8/9, based on the maturity of simplistic waypoint navigation and line-of-sight and satellite communications control. Shore-Based Coastal UMS requires more maritime interaction, i.e., sense and avoid technologies, which is currently less mature at TRL 4-6, meaning operational prototypes are being tested in a relevant environment [13]. For UUV's, long-range underwater communications are also currently at lower TRLs [15], approximately TRL 4. This brings out an important consideration for TRL, although long-range underwater communications are not currently at higher readiness, glider-based UUVs typically surface for communications which is technologically mature.

Launch and Recovery: All three alternatives have feasible launch and recovery mechanisms that are currently at TRL 9. Many current operational UMS comparable to USCG alternatives are man-portable, with the possible exception of Cutter-Based Tactical UUV which is typically launched via ship.

Sensors: Sensing is an area where UMS technologies are currently a limiting factor. Sensor technologies correlate closely with perception capabilities, with a wide range of needs for each UMS alternative. Broadly, these sensor systems can be divided between two categories: Cooperative sensor systems such as Vessel Monitoring System (VMS) and Automatic Identifi-

cation System (AIS), where only participating parties are monitored, and non-cooperative sensor systems such as Synthetic Aperture Radar, optical imaging systems, acoustic surveillance, electronic intelligence (ELINT) where participating is not required but information is often limited [31]. The cooperative sensor system technologies mentioned previously are currently TRL 9, but non-cooperative sensor systems are too diverse to assign a single TRL.

For Cutter-Based Tactical UUV and Off-Shore Strategic USV, a major technology is the acoustic surveillance-enabled vessel identification and classification. This is currently at TRL 6, where proof-of-concept experimentation has been able to detect and classify marine mammals, and would require an approximate $2 million one-time cost for USCG applications based on personal communication with the USCG Research and Development Center. Shore-Based Coastal UMV sensor technology is generally at TRL 8 or 9 depending on the application. For instance, most imaging sonar for hull inspection and survey is currently TRL 8 and 9 [46].

While technology is often an enabler of capabilities and overall system feasibility, there exists a risk of equating demonstrated technology with successful operational systems. Even today, every USCG UMS alternative has some TRL 9 components and it is anticipated that most components will be at TRL 9 within the next ten to fifteen years. In the near-term, it is pertinent for system feasibility to reduce the cost and schedule risks by engaging with technology developers and stakeholders to collaborate on the types of USCG technological needs and the strategies necessary to successfully employ them. In addition, validation of the notional TRLs discussed in this work through test and evaluation and other means is an area of future in-depth analysis.

Another important risk consideration when planning for technology is not recognizing the dynamic fast-paced nature of technological advances. Incorporation of new technologies more frequently in both software and hardware in a modular methodology may be necessary. To mitigate this risk, consideration of an adaption of "agile software development" could provide iterative and incremental improvement.

4.3.2 Capability

Recalling the capability factors discussed in Chapter 2, the USCG capability needs are dynamic with regard to a given CONOP and threat. While these factors are enabled by available and affordable technologies, separate discussion captures the distinct differences between technological enablers and capability factors. This section discusses when the capability factors are anticipated to become suitable for the proposed USCG UMS alternatives. Projected capabilities

also have relationships with policy in regard to the UMS's ability to incorporate new capabilities over its lifecycle, such as collaborative autonomy capabilities anticipated to be realized after 2020 [12].

Alternatives are derived considering current capabilities which allow many of the capability factors to be suitable in the near-term for all alternatives. Persistence, coverage area, timeliness, and perception (to a lesser degree) are among the group of suitable near-term factors. Key challenges in feasibility exist in the factors of command and control (communications), autonomy, environmental integration. The Offshore USV alternative requires overcoming the fewest number of challenges because of its straightforward CONOPS utilizing existing technologies, thereby making it feasible in the near-term. The Shore-Based alternative seeks higher autonomy and environmental integration which is projected to be feasible in the mid-term [12]. Finally, the Cutter-Based alternative requires the most advances in perception capabilities at longer ranges, which also becomes feasible in the mid-term.

Notional capabilities provided in this work inform the feasibility of a given alternative, but system design requirements are more important when developing the actual system. As with technology, some UMS capabilities will require a significant investment of resources to be usable for the USCG. More USCG interaction and investment into critical capabilities will likely mitigate the risk of reduced capability timelines. Also, the gap between what is feasible and practical will be a critical question in the acquisition of UMS.

4.3.3 Policy

The current USCG policy strategy toward UMS from regulatory and operational perspectives remains to be determined. This uncertainty will likely hinder the effective feasibility of any USCG UMS without a concentrated effort to address some critical issues. One central issue is how the USCG will legally enforce and adapt the COLREGS, The Convention on the International Regulations for Preventing Collisions at Sea, 1972, for effective regulation of UMS, both military and civilian . This issue is amplified by need to ensure any USCG UMS is technologically capability and follow operational procedures that comply with said regulations.

While the legalities of UMS are beyond the scope of this work due to a lack of expertise on the subject matter, several assumptions about the current state and its impact on the timeline can be explored. In the comprehensive text *Legal Issues Relating to Unmanned Maritime Systems Monograph*, CAPT Norris provides legal discussion on two key issues: "can such systems be

considered “ships” (“vessels”); and if so, which UMSs further qualify as warships – a term of art which carries with it legal significance?” [57] These issues raise questions about the status of UMS amongest manned vessels and their legal obligations, which could greatly influence the USCG’s ability to procure its own UMS. The COLREGS were historically promulgated for manned vessels, often evolving from complex nuanced criteria for applicability, such as tonnage or fishing [57]. Specific requirements for manned activities such as a Look-out (Rule 5) could be deemed unfeasible by UMS. Considering the nuances within the COLREGS, UMS automation will likely play a large role in their legal status. As remotely, or manually operated UMS being treated as vessels with a human in the loop, and more highly autonomous UMS falling into their own status within the COLREGS. Regardless of the legal status, a projection in the “Envisioned JCA Unmanned System Goals” includes “Automated following COLREGs” within five years [15].

As a comparison to the unmanned air domain, the regulatory body for U.S. airspace, the Federal Aviation Administration (FAA), has greatly limited the airspace that civil and defense Unmanned Aircraft Systems (UAS) can utilize [58]. Although UAS has been an operational technology and provided critical capabilities to the DOD for over a decade, this policy has caused operational limitations and delays. While separate, this example shows that even with a large level of funding and operational need, policy stakeholders may not be capable or willing to adapt their policies in the near-term.

The Cutter-Based UUV and Coastal UUV alternatives are projected to be feasible in the next five years because of limited COLREGS policy concerns for underwater navigation. Also, the representative commercial examples of Offshore USV’s are currently operational with few, if any, COLREGS violations. This supports a slightly delayed near-term feasibility for the USCG. Coastal USVs are the most hindered by the ambiguity in COLREGS policy, because of the often congested areas they operate, which informs a five to ten year timeline for feasibility.

Operational policy presents another challenge for USCG UMS. From strategic placement and mission planning to operator training and qualification, UMS will require a significant investment of resources in policy. The “newness” of UMS will also likely require additional Developmental Test and Evaluation (DTE) and Operational Test and Evaluation (OTE).

Policy will play a large factor is how feasible and successful USCG UMS becomes. The complex nuances of maritime law, especially regarding UMS, provide a large amount of risk in terms of liability and consistency with the law. To mitigate this risk, precise and consistent modifi-

cations or guidance as to UMS with relation to the COLREGS should be adopted. Regulatory stakeholder communication as UMS technology advances will also be important to provide feedback in conjunction with the fast pace of technology.

4.3.4 Supportability and Manpower

Former Chief of Naval Operations, Adm. Gary Roughead, has said "there's no such thing as an unmanned system. There will always be people in the loop, in the process and in some numbers in some way." [59] This notion is vital when evaluating the operational effectiveness, maintainability, and overall affordability of UMS. Each UMS alternative has different manpower needs, dedicated manning, personnel, and training (MPT) and should be analyzed explicitly. These consider the quantity, rates or vocational communities, and qualifications for individuals involved in the UMS. The appropriate composition of these operators will require study but is plausible in the near-term for all alternatives.

Manned-Unmanned Teaming (MUT) is a system relationship established between manned and unmanned vehicles to accomplish a common goal [15]. Near-term issues are largely a function of limited communications capabilities and interoperability issues. As UMS become more complex, long-term issues likely include controlling multiple UUVs/USVs by a single or few operators. Future capabilities antipate the plausibility that UMS could supplant USCG assets as opposed to the current USN doctrine of UMS in a supporting role [57]. As a long-term consideration, this role could fundamentally change the MUT relationship.

The recent news of significant budget and force structure reductions within the USCG and U.S. DoD suggests there will be similar future risks for manpower intensive UMS [15]. To mitigate this risk, the desire for fewer operators and maintainers for a given UMS design should be considered in acquisition.

4.4 Timeline

The analysis provided throughout this work has examined the various aspects of USCG UMS. To communicate the feasibility of those concepts for real-world implementation a timeline for acquisition is presented in this section. It is intended to inform Coast Guard decision makers, in addition to the body of study, about the viability of USCG UMS and motivate future studies and acquisition of proposed alternatives.

4.4.1 Assumptions

The heart of any timeline is the assumptions from which it was developed. For practical application, these assumptions do require continual reassessment from multiple stakeholders to verify and validate their relevance to any USCG UMS program. The following list includes several of this work's assumptions with regard to the developed timeline:

- The rate of technological advancement for both UMS platforms and associated technologies, especially in the areas of communication, networking, autonomy, and sensing, will increase at projected rates [15] [4]. In addition, technology costs will be driven down by advances and economies of scale for an increasing number of users.
- USCG mission priorities and national threats will remain proportional to their current state.
- USCG and other users will become more receptive and capable in operating unmanned systems through increased accessibility, familiarization, and training opportunities.
- Regulatory and policy requirements necessary for operation of UMS will be developed and adopted in tandem with platform acquisition.
- USCG UMS technologies will remain comparable to DOD and commercial UMS, in terms of timeliness and quality.

4.4.2 Acquisition Considerations

In order to provide the most appropriate context for how the proposed USCG UMSs could become a future reality, a discussion of the correlation between USCG acquisition processes and the SE process model utilized in this work is necessary. There are two broad types of USCG acquisitions for any system: Non-Major (less than $300 million life cycle cost) and Major (more than $300 million life cycle cost) [60]. These classifications highlight the importance of affordability in any system acquisition and understanding that systems cost is much more than just the vehicle. Supporting the holistic approach to UMS, the *Major Systems Acquisition Manual* states "A complete system includes processes and people; integration, testing, logistics, and training as well as the human operator, maintainer, supporter and trainer who are all components of the overall system." [60]

Which category of acquisition the USCG UMS alternatives fall under requires an in-depth cost estimation analysis. Considering the fiscal limitations and risk aversion toward new technologies, less costly alternatives may be more feasible. For a Major Systems Acquisition possibility, the Cutter-Based UUV could be included as a complement to a future cutter, much like the UAS

complement to Offshore Patrol Cutter (OPC) [35]. Supplementing an established asset with UMS may be the most feasible, from a cost perspective, for near-term acquisition strategy.

4.4.3 Feasibility Timeline Overview

Drawing from the assumptions and projections discussed in this chapter, observations about feasible time periods to begin acquisition of UMS alternatives can be made. The earliest projected feasibility for each alternative's KSEs is seen as the enabling control gate for system acquisition. As with any timeline or forecast, identification of uncertainty and risk is essential, though projections provide a framework to begin the discussion for a real-world system. Figure 4.4 shows the developed timeline based upon the analysis throughout this work.

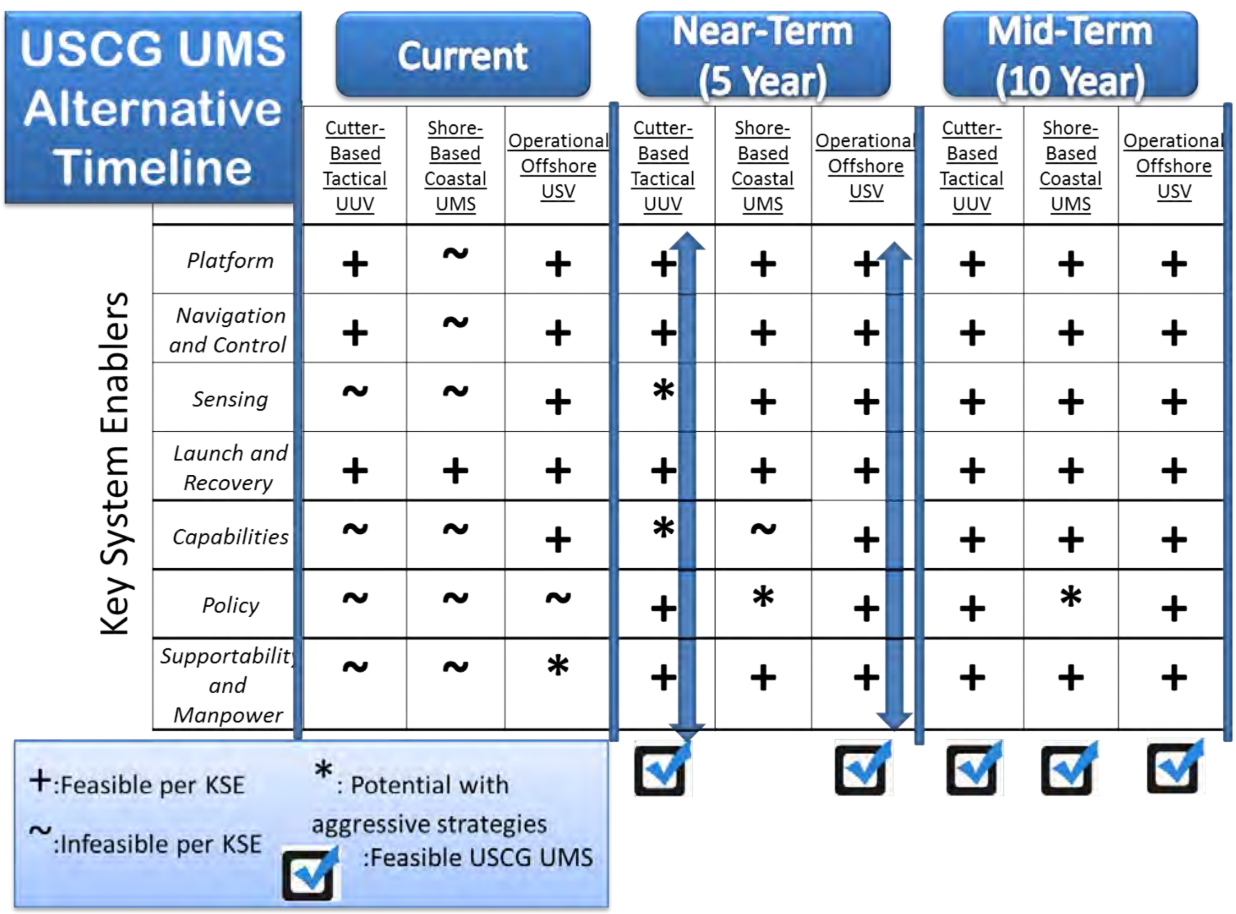

Figure 4.4: The timeline represents the feasibility of alternatives based on the KSEs discussed in this chapter. Asterisks indicate ares of potential feasibility with aggressive strategies.

Currently, no alternatives have sufficient policy in place to be realistically feasible. Operational Offshore USV requires relatively little manpower and support, making its feasibility for this

KSE marginal if it was so desired. Operational Offshore USV also presents the most feasibility in the near-term, meeting all KSE measures to accomplish its CONOPS and providing extended range ISR and MDA for a variety of USCG missions.

Cutter-Based Tactical UUV is also marginally feasible in the near-term if investments are made into advanced perception capabilities for vessel detection and classification. Since perception capabilities are so critical to its CONOPS, the immature of sensing technology limits its feasibility.

Shore-Based Coastal UMS are projected to be feasible in the mid-term primarily due to their complex CONOPS. The need for incorporating less-mature capabilities such as autonomy and environmental integration (i.e., sense and avoid) hinders its feasibility. The immaturity of regulatory and operational policy is also another major factor for this alternative. For this alternative to be feasible sooner, two strategies could be employed; an aggressive approach to policy or modification of CONOPS to reflect acceptance of more limited capabilities or restricted operations.

The timeline assumes an optimistic schedule for USCG UMS feasibility. In addition to the key system enablers it will require proactive Coast Guard leaders that can provide vision and support.

CHAPTER 5:
Conclusions and Recommendations

5.1 Conclusions

This work provided a mission-driven analysis of unmanned maritime systems (UMS) for surface and undersea domains. Drawing from the U.S. Coast Guard's organization structure, jurisdiction, and missions, several motivations were discussed including emerging threats that will challenge traditional USCG assets in the near- and mid-term. Most notably, needs exist for increased USCG and national maritime domain awareness (including undersea), intelligent technology acquisition, and a strategic vision of USCG UMS across domains.

5.1.1 Summary of Findings

In Chapter 1, five research questions were posed that are addressed in the body of this thesis. This section reiterates those research questions with their respective summary of findings and additional insights gained throughout the systems engineering process.

- What USCG missions are best suited for unmanned technologies/platforms?
- Which Concepts of Operations(CONOPS) will best correlate to proposed unmanned systems in the near to mid-term?

Given the broad array of technologically mature or near-mature UMS vehicles currently available for military and civilian applications, capabilities analysis highlighted commonalities with USCG mission needs against today's technology. Within the near- to mid-term, this work identified the USCG missions best suited for UMS to be maritime security mission(s), Marine Environmental Protection, and Living Marine Resources. Although, UMS applications for missions such as Aids to Navigation and Marine Safety are plausible within the mid-term if more aggressive strategic planning is employed.

A consistent set of capability factors was used to relatively rank the CONOPS mission packages against one another. Persistence was seen as the most influential factor given the representative UMS CONOPS, followed closely by perception capabilities. Given the intention to provide multi-mission platforms discussed in Chapter 3, a set of best correlated CONOPS was not explicitly identified in favor of a more holistic capabilities based approach. Fundamentally, the best correlated USCG UMS CONOPS in the near to mid-term were those corresponding to best

-suited missions. Additionally, system considerations beyond capabilities were highlighted. For example the more notional CONOPS such as UMS Aids to Navigation, which leverages proven UMS technological capabilities, are not feasible in the near-term due to policy limitations.

- How can the USCG utilize unmanned systems to enhance capabilities across multiple missions?

The capabilities and concepts informed the three derived USCG UMS alternatives: (1) Cutter-Based Tactical UUV, (2) Shore-Based Harbor/Coastal UMV, and (3) Operational Offshore USV. These alternatives represent a convergence of multi-mission capabilities, (near) proven technologies, and operational areas. Analysis of design and operational characteristics provided additional realism. High-level USCG UMS system architectures, both functional and physical, reinforced the systems approach and relationships between operational, functional, and physical perspectives. The commonality of high-level functions seen in the USCG UMS master functional hierarchy supported the need for modularity of certain UMS technologies, such as acoustic vessel identification and classification. Investment in those types of technologies would provide value across the UMS alternatives. This understanding supports a open architecture development framework seen throughout the UMS industry, and promises to take advantage of commercial and military UMS advances throughout the USCG UMS life-cycle [15].

- Which key system enablers are most significant to the implementation of UMS?
- What is a feasible timeline for UMS Acquisition?

Finally, a survey of existing UMS feasibility documents and roadmaps helped inform the USCG UMS timeline based on the alternatives and key system enablers. This work defined key system enables by technology (including platform, navigation and control, sensing, and launch and recovery), capability, policy, supportability and manpower to incorporate the the majority of system considerations. Interestingly, the vehicle platforms for every alternative are currently technologically ready, although some technological capabilities for perception and power density are still immature. Policy and supportability and manpower considerations are also immature, albeit with less uncertainty than immature technologies. The timeline provides a USCG decision maker with a system-level view of current and anticipated USCG UMS feasibility and identifies areas for additional investment and research discussed in the Recommendations section of this work.

5.2 Recommendations

It is currently feasible and practical to plan for USCG UMS. That being said, this work has emphasized several areas for improvement to best employ these new and innovative technologies. Much like the key system enablers discussed in Chapter 4 the following recommendations can be conducted in parallel to enable a proactive approach to system acquisition. Finally, it is important to consider the need for continual reassessment as assumptions in this work and elsewhere change or are modified, especially when planning for new technologies.

5.2.1 Technology Investment and Partnerships

The USCG should prioritize its UMS technology needs in a central document (i.e., USCG UMS Roadmap) to encourage common and aligned development of service-specific capabilities. Providing a clear vision from senior USCG leadership is essential to acquisition of new untested systems and technologies. Also, maintaining awareness of new technological developments for any future system is a key to success. Due to the USCG's limited budget and expertise in this area, many technologies developed by other stakeholders will add value for USCG applications. Even more value could be added if USCG-specific needs are presented during early stages of technology improvement. As mentioned previously, for example the technological capability of acoustic vessel identification and classification, would be a game-changer for the USCG and for stakeholders throughout the maritime domain and its development could be encouraged through such a vision. Additionally, more UMS on the market will likely reduce the cost and thus increase the ability for the USCG to acquire these systems.

The USCG should enhance its role in partnerships with maritime stakeholders such as the U.S. Navy and academia with regard to UMS. This collaboration would help better inform the choices of USCG decision makers and build a sense of "joint-ness" which is critical to enhancing maritime domain awareness. As a key challenge for DOD unmanned systems, interoperability is another important UMS capability which could be enhanced through additional partnerships. The USN's study of UMS will continue to be a source of useful planning and practical information for the USCG. Due to similarity of missions, especially for maritime security, existing USN UMS could be shared with the USCG through enhanced partnerships.

5.2.2 Policy

The USCG should take a proactive approach and dictate a consistent and cohesive policy for UMS's internal and external use. The quantity and capability of UMS is likely to continue

to grow at an accelerated rate. This fact presents an opportunity for USCG leaders to shape the policy discussion as to how UMS is regulated, and how they will tactically operate their own UMS. Several external stakeholders have made recommendations to the regulation of this aligned topics, and the USCG has been slow to act. As autonomy capabilities increase, the lack of a rapid USCG response will certainly impede and confuse the usage of UMS by all stakeholders. Additionally, USCG undersea regulatory policy should reflect the current nature of the undersea domain and include UUVs in the discussion.

Internally, The timeline discussed in Chapter 4 depicts the surface domain alternatives having less near-term feasibility with regard to policy. This fact is partially due the ambiguity of regulatory standards for all stakeholders, but also points to the need for USCG operational procedures and qualifications to be developed for a new system like USCG UMS.

5.2.3 Operational Testing and Evaluation

The USCG should enhance its operational testing and evaluation of the USCG UMS alternatives and future designs. This work has mostly discussed UMS based on commercially operational system from the prospective of current applications by non-USCG users. There are many unknowns for systems, even with proven technology, that must be thoroughly vetted through operational test and evaluation to fully asses system effectiveness. This process will likely result in several lessons learned that will help iterate the systems engineering process, challenge assumptions, and improve the final UMS.

5.2.4 Build Organizational Knowledge about UMS

The USCG should build organizational knowledge on unmanned technologies and systems. The small size of the Coast Guard officer corps and historically limited interaction with UMS presents a learning curve for implementation. Without fostering this knowledge base, new and innovative USCG applications of UMS are likely to be lagging. Also, the USCG has a need to develop a technical and practical competence surrounding undersea technologies and applications. To provide the most effective regulatory oversight for non-USCG applications and best usage of USCG UMS, this competence will be essential.

5.2.5 Institutional Context

The USCG should acquire new technologies, including UMS, through a variety of mechanisms, including traditional asset support. UMS has the potential to provide a capability

to augment many current and future Major Systems Acquisition assets. These enhanced capabilities could effectively reduce the total number of assets needed. For example, the USCG may require fewer Offshore Patrol Cutters if they were augmented with Cutter-based tactical UUVs. Alternatively as a non-augmentation strategy, Shore-Based Coastal/Harbor UMS could be acquired through a Non-Major Systems Acquisition and provide substantial standalone capabilities. A shift in the USN's use of UMS as supporting technology to independent technologies, provides an interesting future tradespace [57]. USCG UMS acquisition strategies should reflect the unique nature of their applications.

5.3 Future Work

Unmanned maritime systems are complex entities that will require a great deal of follow-on work to implement for the USCG. This work provided a high-level analysis, but several aspects of UMS could not be covered in the depth or diversity needed for a fielded system. This section highlights some of the areas for additional research and analysis that will better develop USCG UMS.

Affordability is a challenge that impacts the full set of key system enablers. Further research should more fully investigate UMS cost per key system enabler and over the system's life cycle. Enabling technology cost estimates would add great value from a timeline perspective. Comparisons to current USCG fiscal and resource allocations may also provide context for the feasibility of USCG UMS alternatives derived in this work.

A more robust stakeholder analysis and interaction would lend better operational and institutional context to this work. Different USCG communities have their own priorities and needs, and future studies should incorporate the operators' perspective even before operational test and evaluation. For instance, the use of the marine safety mission package's UUV to remove bio-fouling from USCG cutters may prove to be a long-term cost saving strategy for the afloat community. Non-USCG stakeholders, such as UMS designers, could provide additional feasibility and cost information.

Interoperability studies and USN UMS mission overlap should be investigated. Communication of information in the maritime domain is often redundant, even within the U.S. Armed Forces. For maximal effectiveness, a United States UMS should strive to share MDA with as little redundancy as possible. Research into multi-asset multi-domain (i.e., UAV, UUV, Cutter) information sharing would enhance USCG UMS planning.

UMS tactics and operational strategy are important policy objectives for system success. Key areas of interest include the configuration of UMS in regard to type, quantity, and formation for tactics. Additional emphasis on operations analysis provides additional mathematically-grounded support for future decisions and mission planning.

Use of modeling and simulation for USCG UMS alternatives would be useful in deciphering the complex and confounded set of factors. Comparisons to manned assets could be better quantified and assessed as well.

System suitability will also play a large role in UMS feasibility. More detailed analysis of its factors including reliability, availability, and maintainability, in addition to specification of UMS design requirements, would build upon this work's provisional estimates.

5.4 Conclusion

The U.S. Coast Guard's (USCG) long history of success can, in some measure, be attributed to one of the service's core principles: flexibility [1]. From its earliest roots in 1790 as the Revenue Marine (later called the Revenue Cutter Service), this principle has allowed the USCG to adapt to whatever mission(s) the nation has needed. Unmanned Maritime Systems are just one technology among many that provide capabilities that can counter the emerging threats anticipated in the coming decades. By evaluating UMS application from a top-down mission perspective, the service's effective needs inspires a value-added use of technology. Commonality of missions and multi-mission platforms aids in the flexibility of UMS to benefit many different communities and thus the USCG as a whole. While feasibility and readiness are key questions for USCG UMS, the derived alternatives in this study represent technologically mature platforms today. The developed near- to mid-term timeline provides a baseline for USCG decision makers to leverage, in tandem with the recommendations presented in this chapter. As such, this work has provided a strong foundation for unmanned maritime systems for the U.S. Coast Guard with a wide array of applications that should motivate the future acquisition of USCG-specific systems.

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